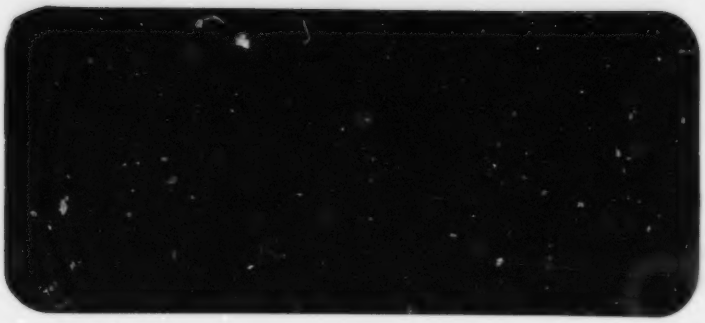

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LIMITATIONS OF ESTIMATING ICE LOADS FROM THE DYNAMIC RESPONSE OF A MASSIVE BRIDGE PIER

By

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ABSTRACT

A numerical model which originally used Fourier transforms to calculate ice forces from measurements of bridge pier accelerations was modified because it did not work well for data sets longer than one second. The modified model uses a double integration technique to solve the single-degree-of-freedom system which was used to describe a massive pier near Hondo, Alberta. This report evaluates the effectiveness of using this modified model to calculate ice forces for long duration crushing events.

Three major concerns were addressed when the double integration model was developed: integration accuracy, baseline determination, and data precision. Tests of both synthetic data sets and measured accelerations showed that the optimal characteristics of the model given the available hardware were: trapezoidal integration, linear regression for baseline approximation and a time step of 0.5 milliseconds.

Five events, with durations ranging from two seconds to five seconds, were analyzed using the optimized model. From this analysis, it was found that the model could accurately calculate load events up to three seconds long. Serious error occurred in the results of events with durations longer than three seconds, likely due to inaccurate baseline determination or possibly extraneous data in the acceleration data set.

The use of this model to obtain peak ice loads is of limited value because the peak load events often have durations which are longer than three seconds and the model can not accurately calculate loads longer than three seconds. It may be possible, however, to use this model for small streams where short duration impact loads are the dominant events.

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The project was originally started by C.J. Montgomery and A.W. Lipsett and later continued by W.J. Huiskamp. T. Ridgway, P. Mostert, B. Trevor and J. Thompson collected the data and answered numerous questions about equipment and field techniques. P. Mostert also set up the FM tape recorder and strip chart recorder for the digitizing process. V. Arora wrote and modified the digitizing program while L. Chase connected the necessary computer hardware. Thanks to R.W. Kornelsen of Alberta Transportation for his support of this project. Special thanks to D.D. Andres for his guidance and the review of this report. The manuscript was typed by C. Reitzel.

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1.0 INTRODUCTION

1.1 Background

Structures erected in water bodies in cold regions can be subjected to considerable forces when struck by moving ice. Although field measurements of these ice forces have been attempted since the late 1800's, the amount of data available is still relatively sma'l and of questionable quality (Neill, 1976). Much of this data was collected using measurement systems composed of load cells or strain gauges connected to load beams or load plates placed in the path of the ice. These systems, which directly measure the ice loads, are costly to install and cannot be easily moved from one site to another, hence, the limited availability of data. Also, the dynamic response of the measurement system may modify the data so that the actual ice forces may not be represented accurately by the resultant force history.

The disadvantages of direct force measurements can be overcome by measuring the dynamic response (acceleration) of a structure and then calculating the force required to produce this response (Montgomery and Lipsett, 1981). Once a model describing the ice-structure interactions has been developed, ice forces could be determined from data produced by relatively inexpensive accelerometers mounted on the structure.

Most studies of the dynamic interaction between structure and ice have been aimed at developing models to simulate the structural oscillations observed during ice loading events. Matlock, Dawkins, and Penak (1971) proposed a computer model which treated ice-structure interactions as single-degree-of-freedom (SDOF) systems acted on by periodic forcing functions. Sundararajan and Reddy (1973) combined this model with a Fourier analysis technique to express real ice force histories in terms of frequency. They found that the response of their system was greatest at frequencies near or below the natural frequency of the structure. This model was later improved by substituting a multi-degree-of-freedom (MDOF) system for the SDOF system (Reddy, Swamidas and Cheema, 1975). Further, Määtänen (1977) used a MDOF model which was solved using a

finite element technique to describe the dynamic response of a lighthouse in the Gulf of Bothnia. He found close agreement between the dynamic response computed using his finite element technique and the dynamic response measured using accelerometers.

The above studies established that dynamic response could be computed from ice force measurements but it was Engelbrektson (1977) who demonstrated that the reverse was possible; that ice forces could be calculated from acceleration measurements. Acceleration measurements were input into a SDOF model describing the dynamic response of a lighthouse and numerical integration was used to solve for the ice forces. Montgomery, Gerard and Lipsett (1980) developed a similar technique to indirectly measure ice forces on bridge piers. A SDOF model describing the pier vibration was solved using Fourier transforms. Comparison of the results of this model with force measurements obtained from a load cell demonstrated that the model only worked properly for load events with durations of less than one second (Van Der Vinne, 1988).

1.2 Objectives

Previous attempts to evaluate the suitability of using a single-degree-of-freedom numerical model of bridge pier vibration to convert acceleration measurements into ice load data produced some promising results but also revealed some serious limitations (Van Der Vinne, 1988). The model accurately reproduced the shape of load events with durations of less than one second, although it overestimated the magnitude by about 30% compared to load cell measurements. These short duration events consisted of impact loads and bending failures. Crushing failures could not be analyzed accurately because the extended durations of these events increased the likelihood of errors occurring.

Since the crushing failure mode is often the dominant failure mode during ice runs, it was felt that a continued attempt to develop a technique which could handle these longer duration events was justified. This report attempts to evaluate the suitability of using a modified numerical model to convert longer duration acceleration records into ice

load data. The model was modified by substituting a numerical integration technique for the Fourier transform technique of the original model so that the events could be split into more manageable segments. An additional benefit of the numerical integration scheme is that there is less data manipulation needed, therefore the sources of error can be more readily determined.

This report describes the Hondo installation and discusses the theory behind the numerical integration model. It also addresses the three main problems encountered in developing the new model: baseline drift, integration accuracy, and data integrity. The modified model is evaluated by comparing the ice forces generated from the acceleration data with the ice forces obtained form corresponding load cell data.

2.0 INSTRUMENTATION

2.1 Site Description

The piers of the bridge which spans the Athabasca River near Hondo, Alberta (figure 1) are subjected to ice loads each year during spring breakup (Lipsett and Gerard, 1980). The ice thickness before breakup ranges from about 0.15 m to 1.45 m with the thickest ice originating in the bend upstream of the bridge. The ice strengths, measured with field compression tests on 100x100x200 mm blocks, were highly variable, ranging from 350 kPa to 4000 kPa. The flow velocity at break-up is typically about 1.6 m/s, although it has been observed as high as 2.9 m/s. Fast moving floes of thick, strong ice produce the largest ice loads.

The magnitudes of the ice loads and the types of failures depends on the properties of the ice at the time of breakup. The failure mode determines the frequency and duration of these ice loads. Crushing failures produce the highest frequency load histories, the frequency probably being related to the ice crystal diameter. They also produce loads with the longest duration. Bending failures generate lower frequency loads which have periods related to the time taken for the ice to ride up the pier before breaking. Impact loads and splitting failures produce sharp peaks with short durations.

In 1966, one of the piers of the Hondo bridge was instrumented to measure ice forces. A side view of this concrete pier is shown in figure 2. The ice loads were measured directly using a specially designed nose section incorporated into the pier during construction. This steel encased, reinforced concrete nose with a semicircular cross-section, is pinned near its base, while a commercially available load cell supports the top and measures the reactions to the ice forces. This load beam is 2.32 m wide and inclined 23 degrees to the vertical.

The fundamental natural frequency of the load beam is 57 Hz. This is above the frequency range of the ice forces, so no resonance should occur. A shaft provides access to the load cell and a stilling well in

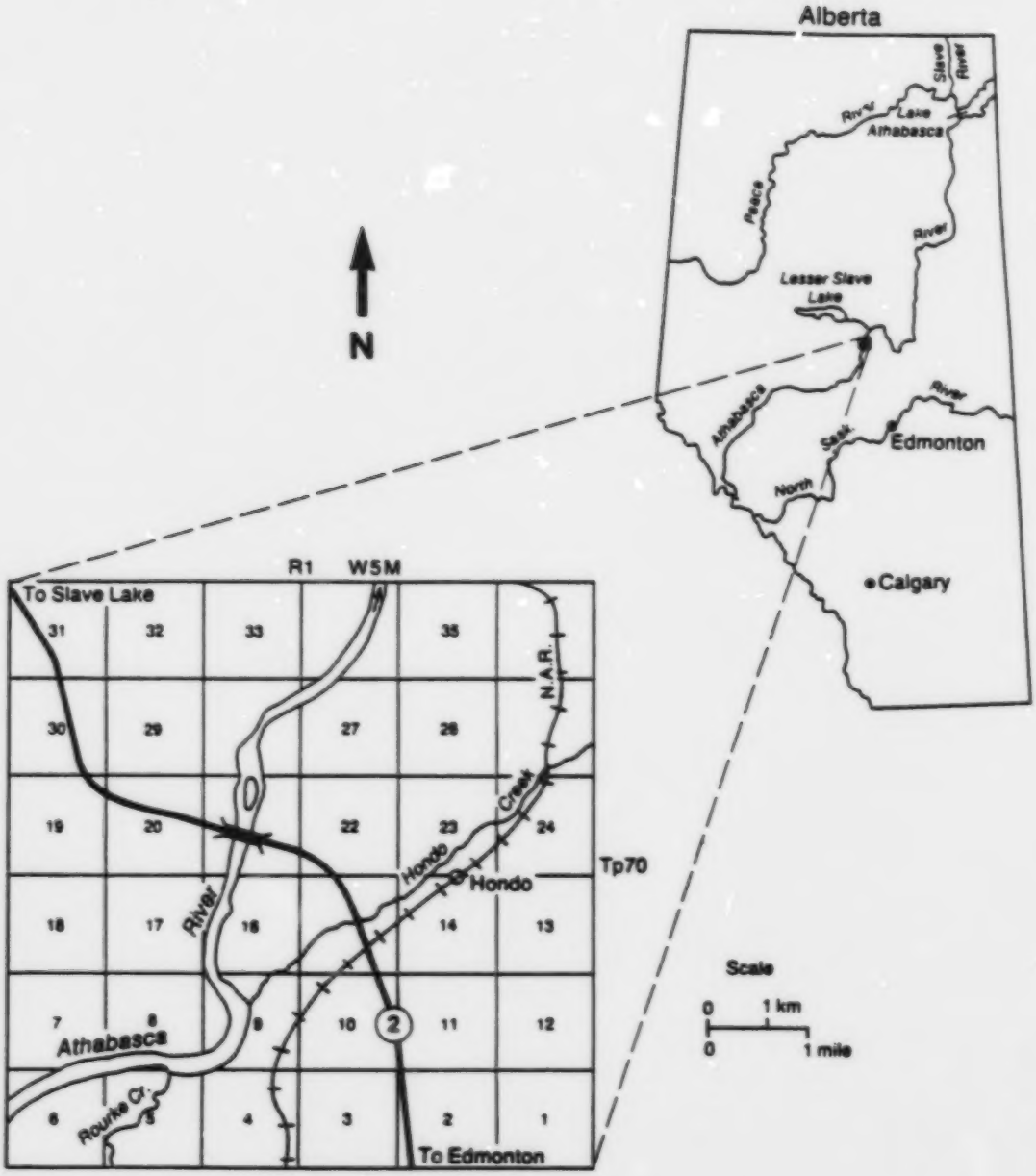

Figure 1 Location of Hondo installation.

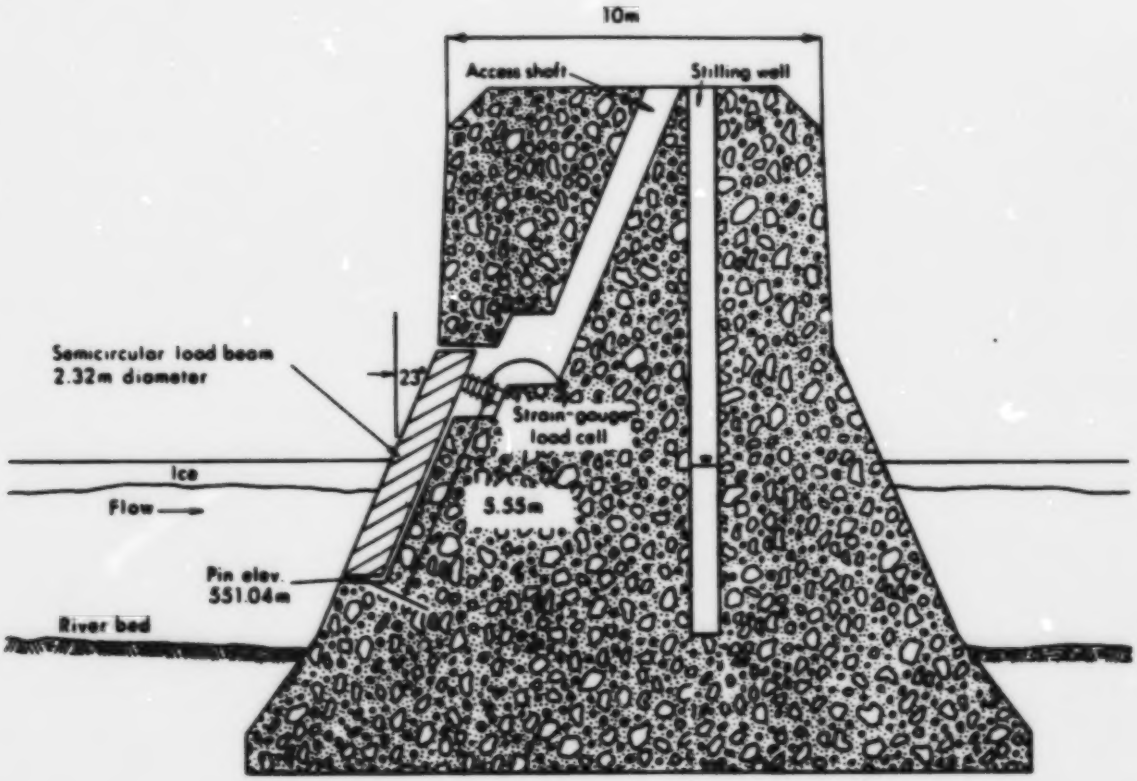

Figure 2 Cross-section of Hondo bridge pier.

the center of the pier contains a float and recorder to monitor the water level in the river during the ice runs.

The dynamic response of the pier was measured using accelerometers placed on the pier. A strain gauge accelerometer with a sensitivity of 0.2 volts/g was installed on the pier in 1977 but this is not sensitive enough to measure the streamwise accelerations accurately. In 1978, two strain gauge accelerometers, each with a sensitivity of 2.5 volts/g were mounted on the top of the pier, one measuring longitudinal accelerations and the other measuring transverse accelerations.

2.2 Dynamic Characteristics of Pier

Three characteristics - mass, damping and stiffness - are needed to theoretically determine the dynamic response of a structure. The mass of the Hondo test pier was calculated from the bridge plans, while field tests were performed to determine the damping and stiffness constants (Montgomery and Lipsett, 1980). Coefficients for damping and stiffness were measured for two degrees-of-freedom: translation along the streamwise longitudinal axis and rotation about the transverse horizontal axis. The values of these characteristics are given in table 1.

Table 1 Dynamic characteristics of the Hondo pier

Characteristic	Value
mass, m (kg)	2.0×10^6
mass moment of inertia, J (kg·m²)	1.5×10^6
translational stiffness, k_x (kN/m)	6.2×10^6
rotational stiffness, k_θ (kN·m)	9.3×10^9
damping coefficients	
longitudinal, C_{xx} (kN·s/m)	3.9×10^4
mixed, $C_{x\theta}$, $C_{\theta x}$, (kN·s)	-1.9×10^4
rotational, $C_{\theta\theta}$ (kN·s·m)	6.8×10^5
moment length, 1 (m)	7.3

The Hondo pier was found to respond primarily in the longitudinal translation mode. The fundamental natural frequency of the pier in this mode, calculated from the mass and the longitudinal damping and stiffness coefficients, is 8.9 Hz. Resonance occurs when a load history has a similar frequency, but the risk of extreme oscillations of the pier is reduced due to the high damping ratio, which is 0.19.

3.0 THEORETICAL BACKGROUND

3.1 Single-Degree-of-Freedom System

The simplest method of analyzing the dynamic response of a system is to treat it as a single degree-of-freedom system. If the primary translational vibration response is dominant, the system can be modeled by the one dimensional motion of a mass, m, under the influence of a forcing function, F(t), a spring, k, which resists the motion and a dashpot, c, which damps the motion as shown in figure 3 (Clough and Penzien, 1975). The differential equation describing the displacement of the mass as a function of time, x(t), is:

$$[1] \quad mx''(t) + cx'(t) + kx(t) = F(t)$$

where $x'(t)$ is the velocity of the mass and $x''(t)$ is the acceleration of the mass.

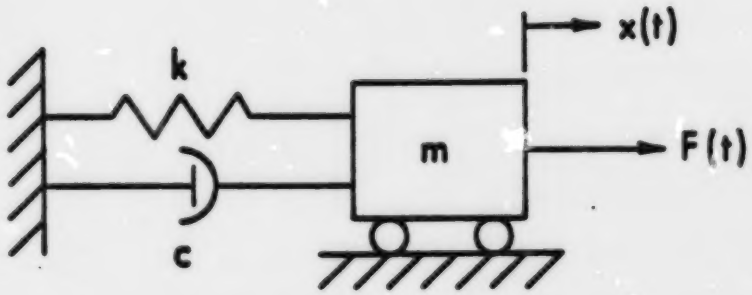

Figure 3 Single-degree-of-freedom system.

A multi-degree-of-freedom (MDOF) system should be used if other modes of vibration are significant. If, for example, rotation about the transverse horizontal axis is significant, equation 1 must be solved simultaneously with another equation describing the rotational motion. The Hondo pier was found to vibrate primarily as a single-degree-of-freedom system (Montgomery and Lipsett, 1980), so only this mode of vibration was measured.

Two methods of solution can be used to obtain the force history, F(t), from equation 1 if only the acceleration history, x"(t), is known. The first method, the Fourier transform method, is described in an earlier report (Van Der Vinne, 1988). The second method, the numerical integration method, involves integrating the acceleration once to obtain the velocity history, x'(t), and then integrating again to obtain the displacement history, x(t). The force history can be computed by substituting these integration results into equation 1. An advantage of this procedure is that each step is physically meaningful, the results can be tested against reality. For example, after the load is removed, the velocity and displacement should return to zero. If they do not, there are errors in the results. A disadvantage of this technique is that errors introduced during the first numerical integration may be magnified when the second integration is performed. Therefore, numerical integration errors must be kept to a minimum.

3.2 Numerical Integration Techniques

The integral of a function can be determined by calculating the area under the curve describing the function. This area must be found numerically when the function is defined by a set of discrete data points. Since the function is not defined between consecutive data points, some method of interpolation must be used. Numerical integration techniques differ in the method of interpolation used.

3.2.1 Trapezoid Technique

The trapezoid technique uses linear interpolation to define the

function between consecutive data points, therefore only two data points are needed to calculate the integral. The integral value, x_j, corresponding to the data value x'_j, is calculated using the equation:

$$[2] \quad x_j = x_{j-1} + (x'_j + x'_{j-1}) \cdot \Delta t/2$$

where Δt is the time step between the data points x'_{j-1} and x'_j. The previous value of the integral, x_{j-1}, is calculated during the previous time step. The error in this procedure will be of the order Δt^2 so the use of smaller time steps produces less error. An advantage of using this technique is that the function being integrated need not be continuous; that is, the technique still works if there are abrupt changes in the digitized data. A disadvantage is that the digital record may not be representative if the data fluctuates rapidly within a few time steps; the peaks of the actual data record may be truncated during the digitizing process and these errors may accumulate during integration.

3.2.2 Higher Order Techniques

Higher order integration techniques use curvilinear interpolation to define the function between data points. This means that more than two data points are needed to calculate the integral at a given point. One such higher order scheme for which the fortran code was readily available is a combination of Simpson's rule and Newton's 3/8 rule:

$$[3] \quad x_j = x_{j-5} + [x'_{j-5} + 3.875 \cdot x'_{j-4} + 2.625 \cdot x'_{j-3} + 2.625 \cdot x'_{j-2} + 3.875 \cdot x'_{j-1} + x'_j] \cdot \Delta t/3$$

where six data points are needed to define the integral at a given point. Although this equation produces a truncation error of the order Δt^5, which is much smaller than the truncation error of the trapezoid technique, the function must be continuous and differentiable therefore smoothing of rapidly fluctuating data values may be required.

4.0 MODEL DEVELOPMENT

Model development can be divided into three main stages. The first stage involved testing the numerical integration techniques to determine which was the most accurate for this particular application. During the second stage, a number of regression schemes were evaluated to see which one best approximated the acceleration baseline. In the third stage of model development, various time and voltage increments were used in the digitizing process in order to determine the data precision needed to produce the best model results.

4.1 Integration Techniques

Both of the numerical integration techniques described in the previous section, the trapezoid technique and the higher order technique, were tested for accuracy before one technique was selected for use in the model. Data describing a simple cosine function was used as input for the tests. A cosine function was used because the exact solution of the double integration of this function is known to be a negative cosine function. Thus, the results of the numerical double integration tests could be compared with the exact solution to determine the accuracy of the techniques.

The accuracy of the numerical integration techniques was found to be dependent on the frequency of the input data. Three different data frequencies were tested: 5, 10 and 20 data points per cycle. When 20 data points per cycle was used in the tests, both numerical integration schemes produced results with less than 0.5% error (figures 4 and 5). The results were much the same when 10 data points per cycle was used as input (figures 6 and 7); but, when 5 data points per cycle was used, large errors resulted. The trapezoid technique produced accurate peaks but the troughs were in error by more than 60% because the peaks in the input data were truncated (figure 8). The errors produced by the higher order technique were large as well and the error accumulated over the five cycles of data (figure 9). When the input data was smoothed to make the data continuous and differentiable as this technique requires, the

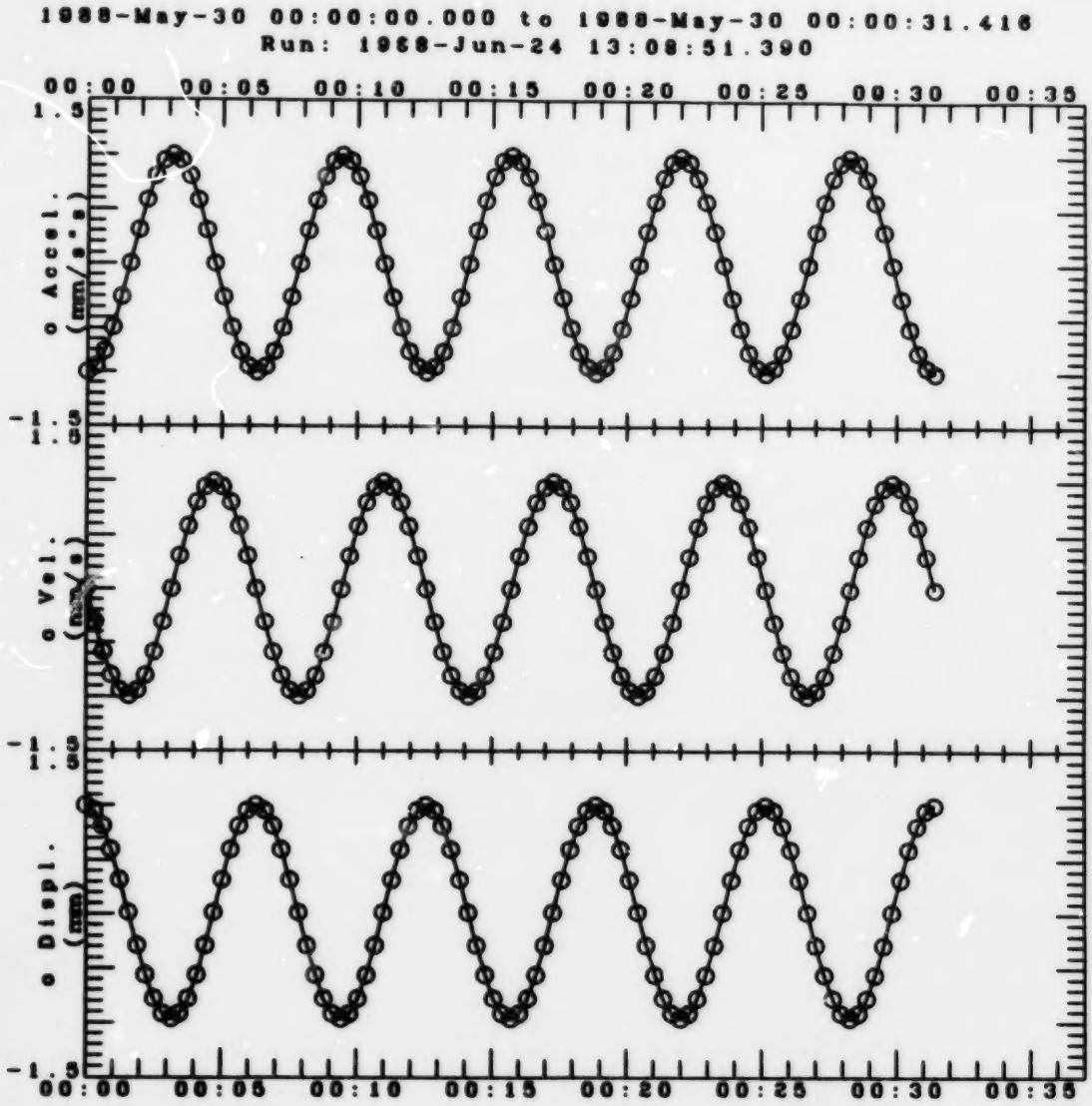

Figure 4 Double trapezoidal integration of a cosine function digitized at a rate of 20 data points per cycle.

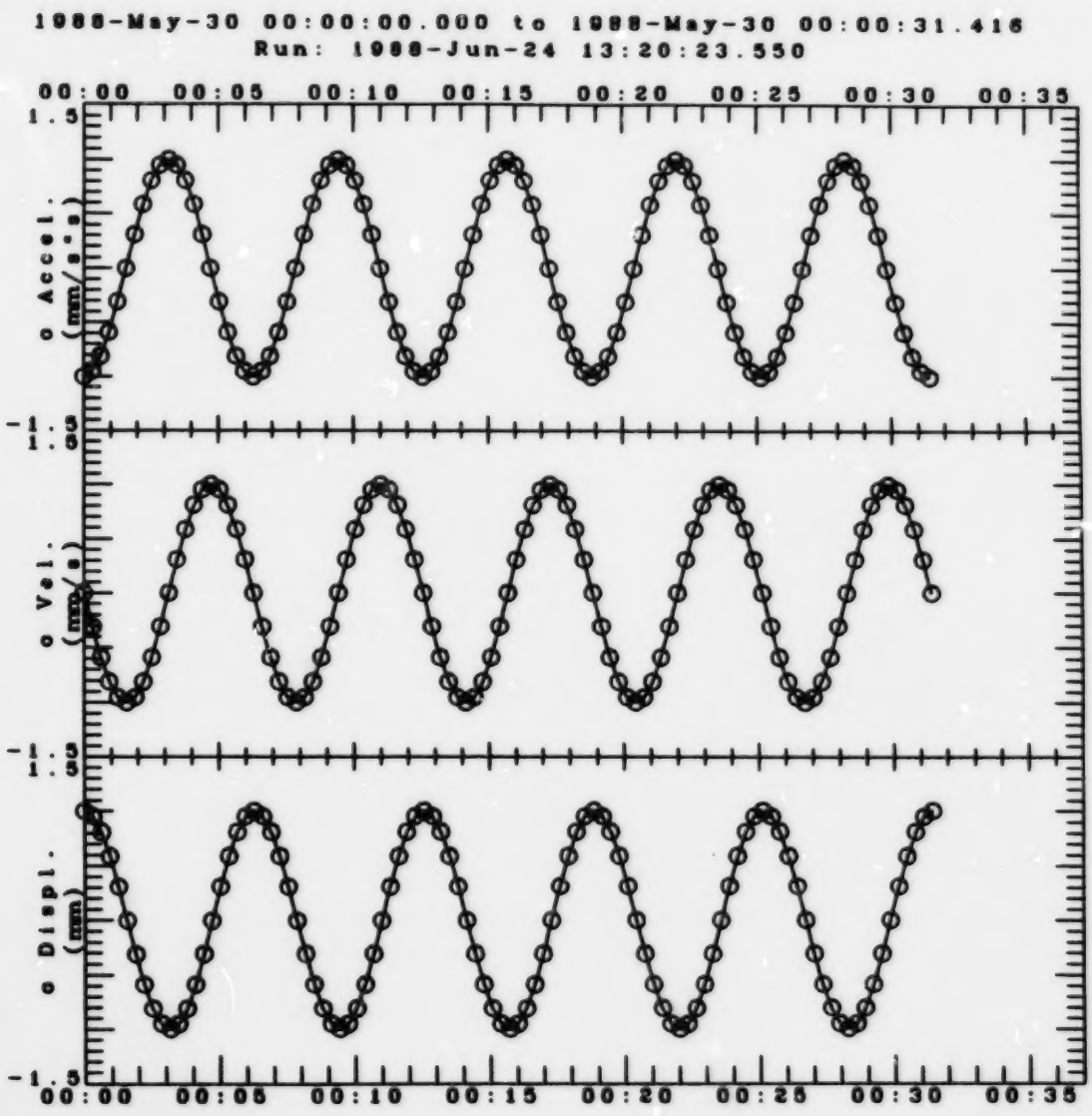

Figure 5 Double high accuracy integration of a cosine function digitized at a rate of 20 data points per cycle.

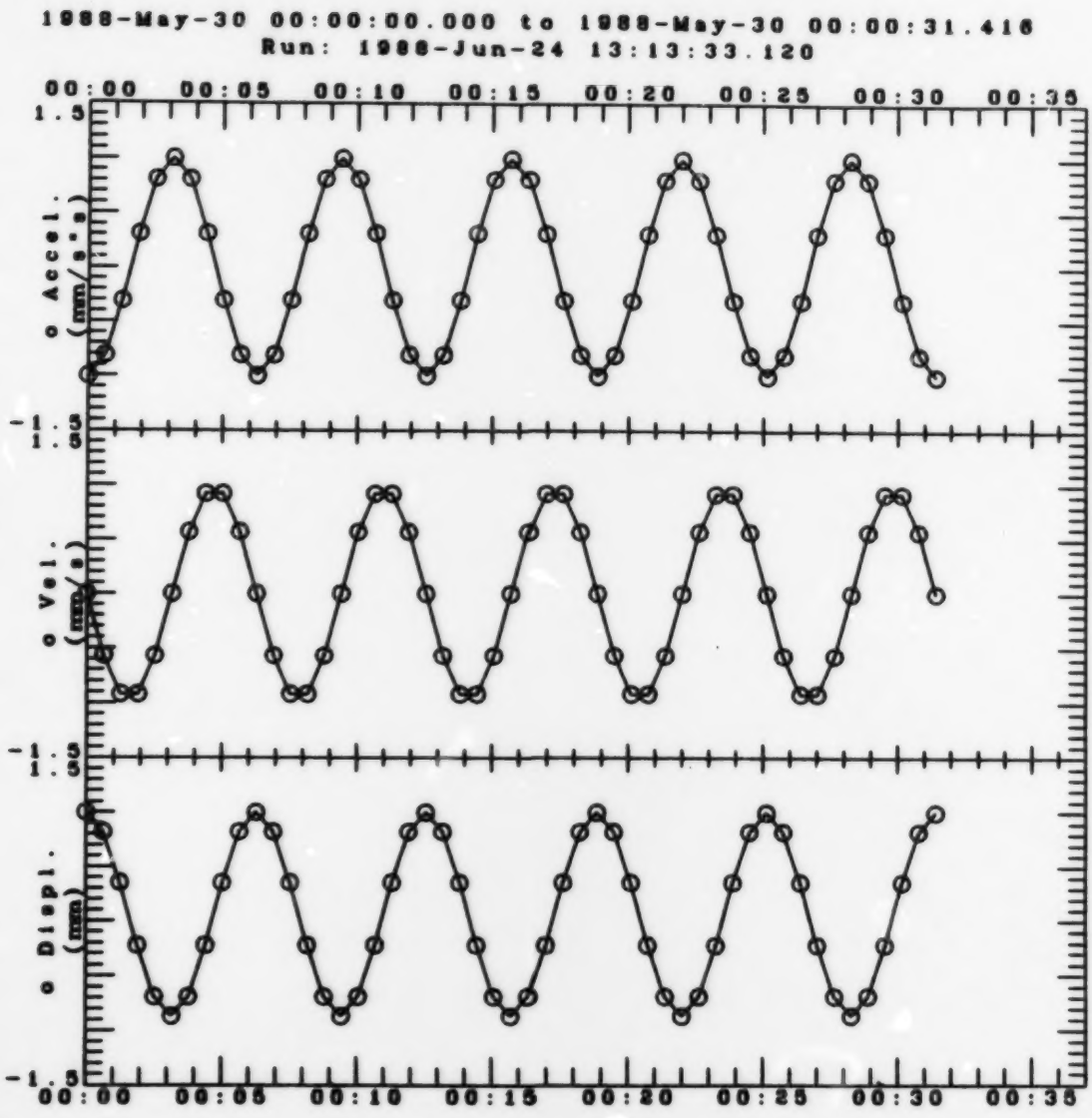

Figure 6 Double trapezoidal integration of a cosine function digitized at a rate of 10 data points per cycle.

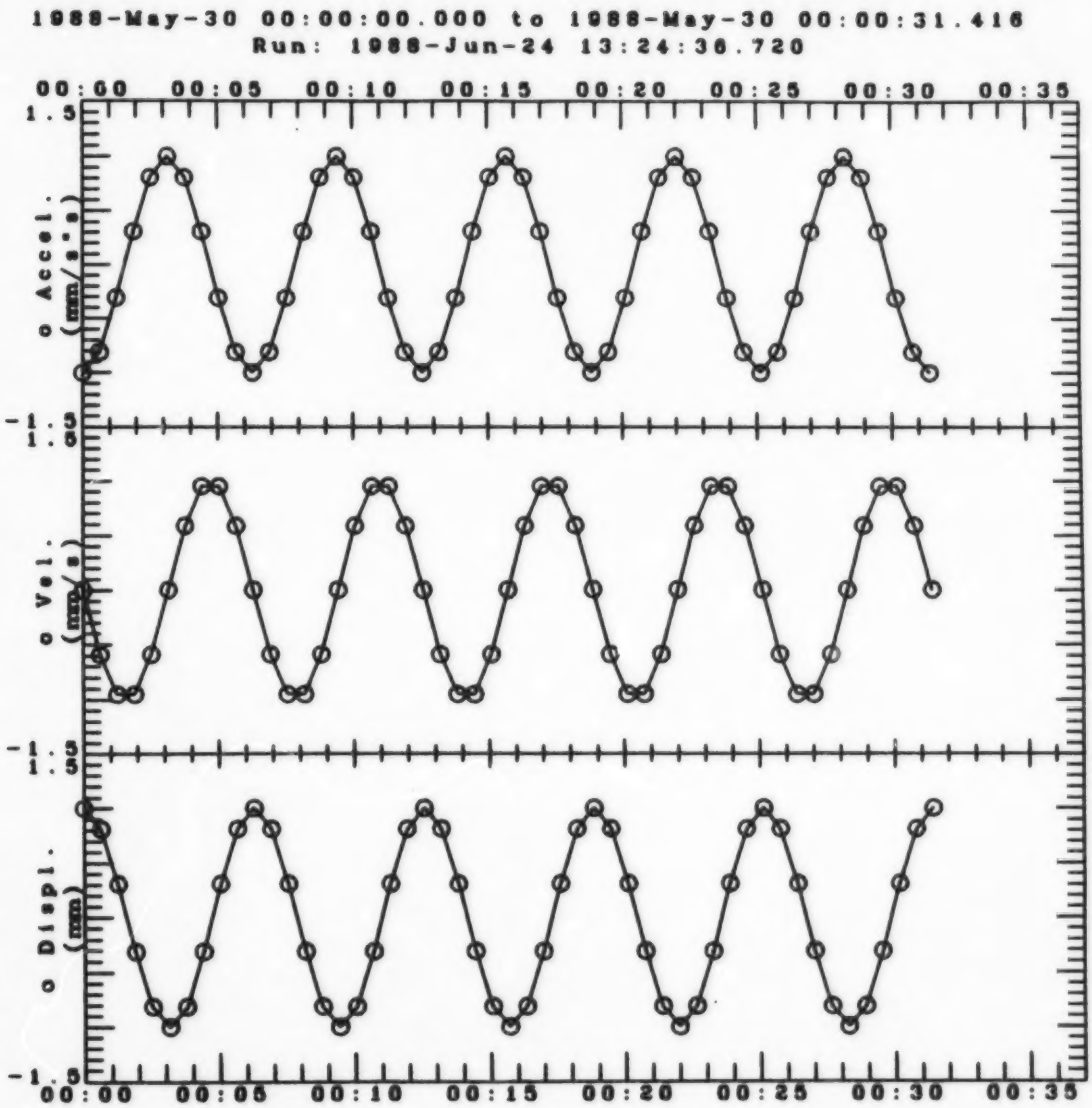

Figure 7 Double high accuracy integration of a cosine function digitized at a rate of 10 data points per cycle.

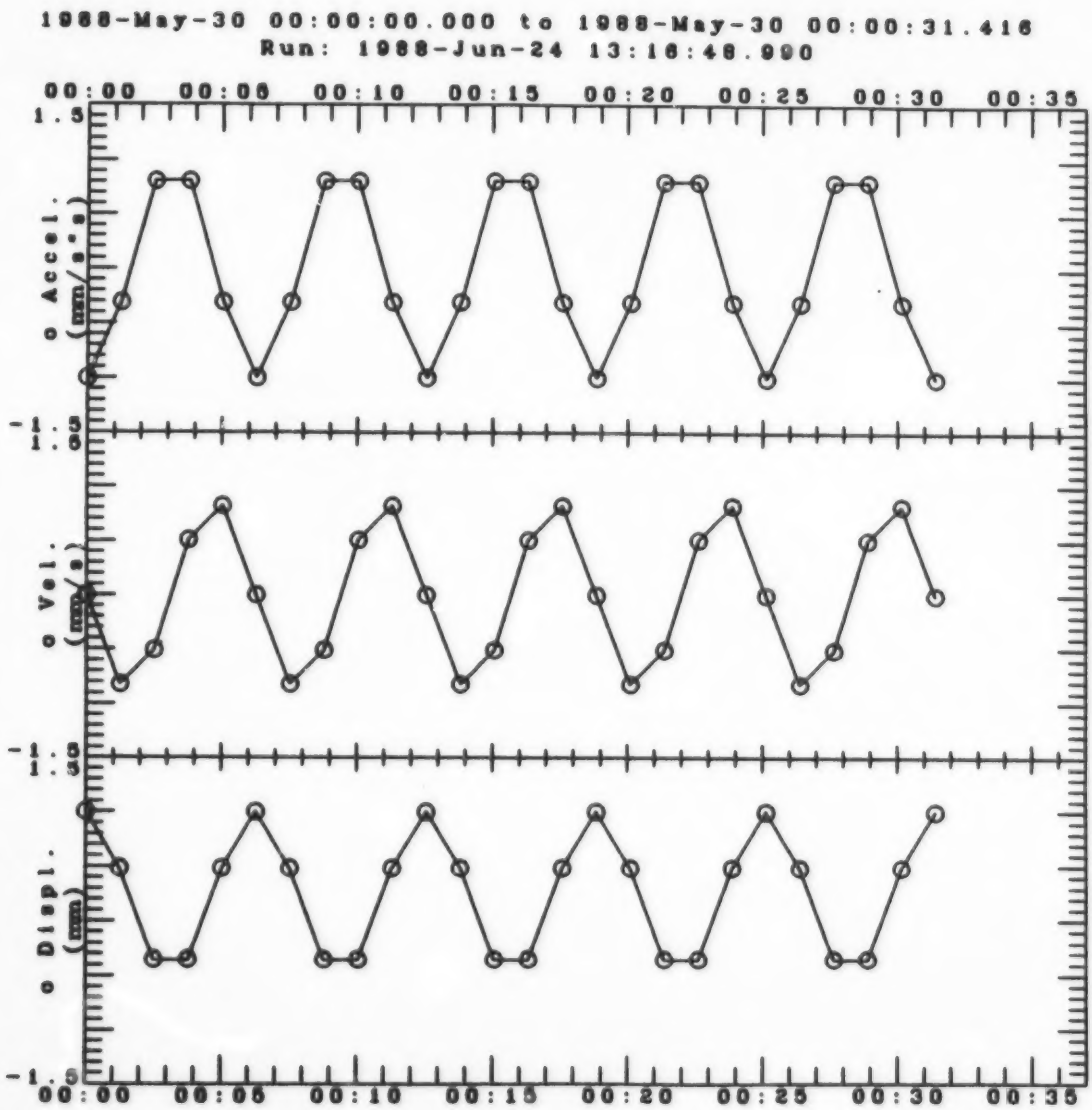

Figure 8 Double trapezoidal integration of a cosine function digitized at a rate of 5 data points per cycle.

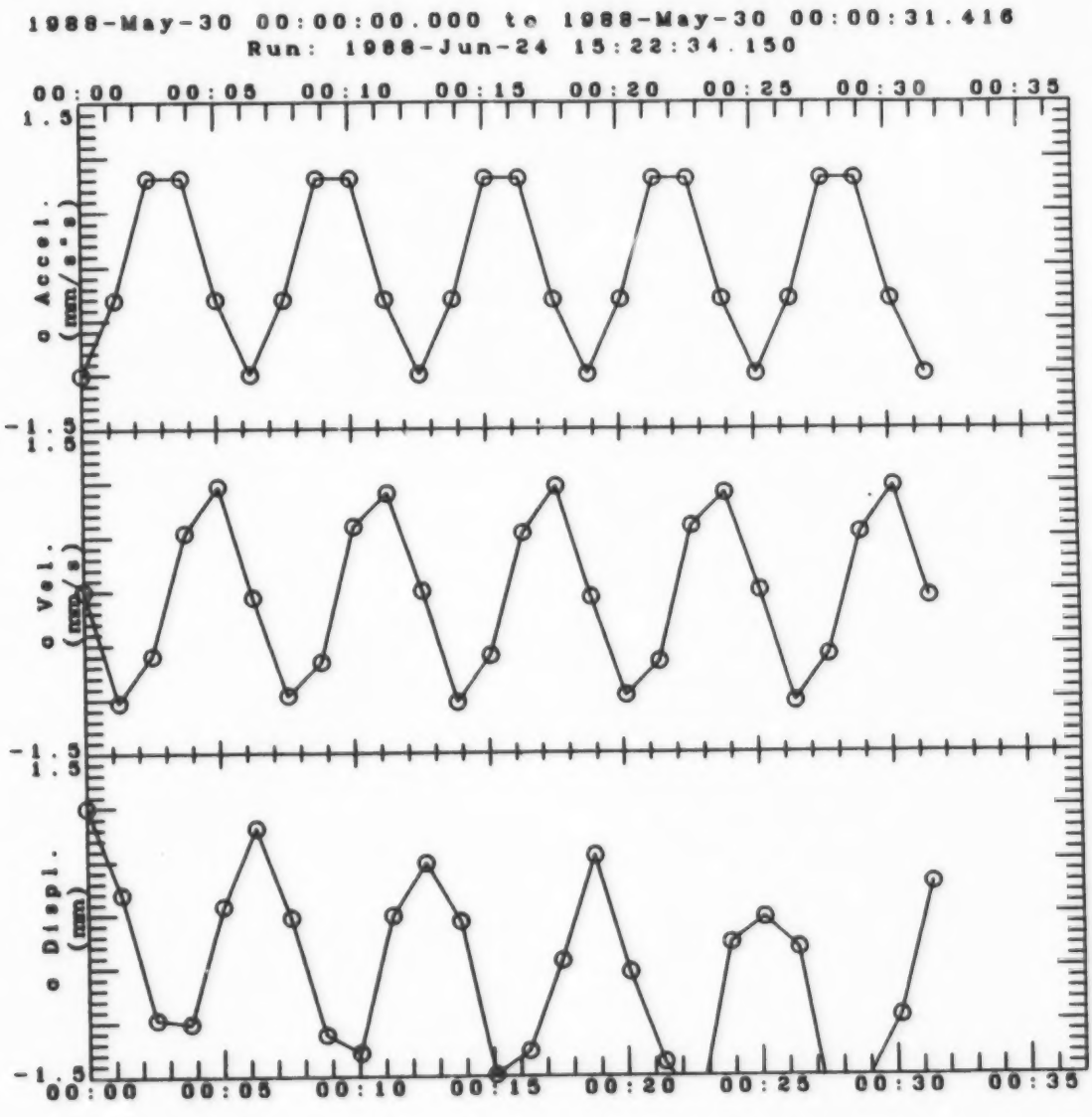

Figure 9 Double high accuracy integration of a cosine function digitized at a rate of 5 data points per cycle.

errors were even greater because smoothing reduced the peaks of the input data (figure 10).

The trapezoid technique was chosen for use in the model because the errors were not cumulative and the data did not require smoothing.

4.2 Baseline Determination

The baseline, or zero acceleration, value of the accelerometer can vary slightly with time. The baseline drift must be removed from the data before integration can be performed, otherwise the integration will magnify the drift, producing large errors in the displacement. Some methods of determining the acceleration baseline include: linear regression, segmented linear regression and curvilinear regression.

If the baseline drift is approximately linear over the duration of an event, linear regression of the accelerations can be used to determine the baseline. Once this regression line has been subtracted from the data, the accelerations can be integrated without generating huge errors. Without linear regression, the calculated load histories would not even remotely resemble the measured load histories; the peak loads would be more than ten times what they should be. When linear regression was used to remove the baseline drift, as it was in figure 11, the velocity and displacement histories, as well as the calculated load histories, return to zero at the end of a the event as they should. In figure 11, the first part of the calculated load history resembles the measured load history; although in the later part of the event, physically impossible negative loads appear in the calculated load history.

A more complex method of determining the baseline is needed if this difference is caused by non-linear baseline drift. Segmented linear regression was used in an attempt to analyze data with non-linear baseline drift. The events were divided into a number of equal segments and linear regression was performed on each of the segments using the end point of the previous segment as the origin. This method of baseline removal did not work well because significant errors were produced at the

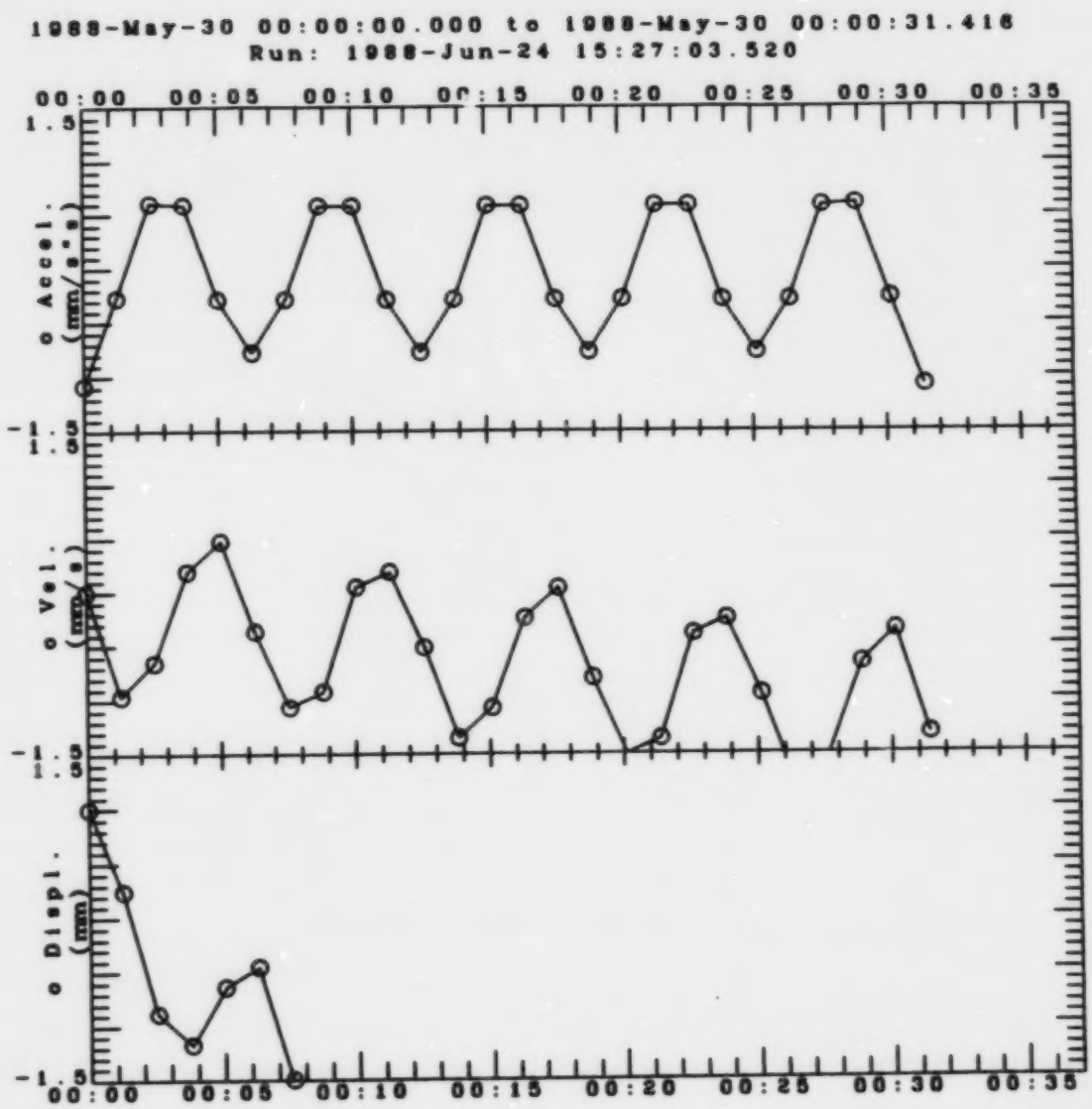

Figure 10 Double high accuracy integration of a smoothed cosine function digitized at a rate of 5 data points per cycle.

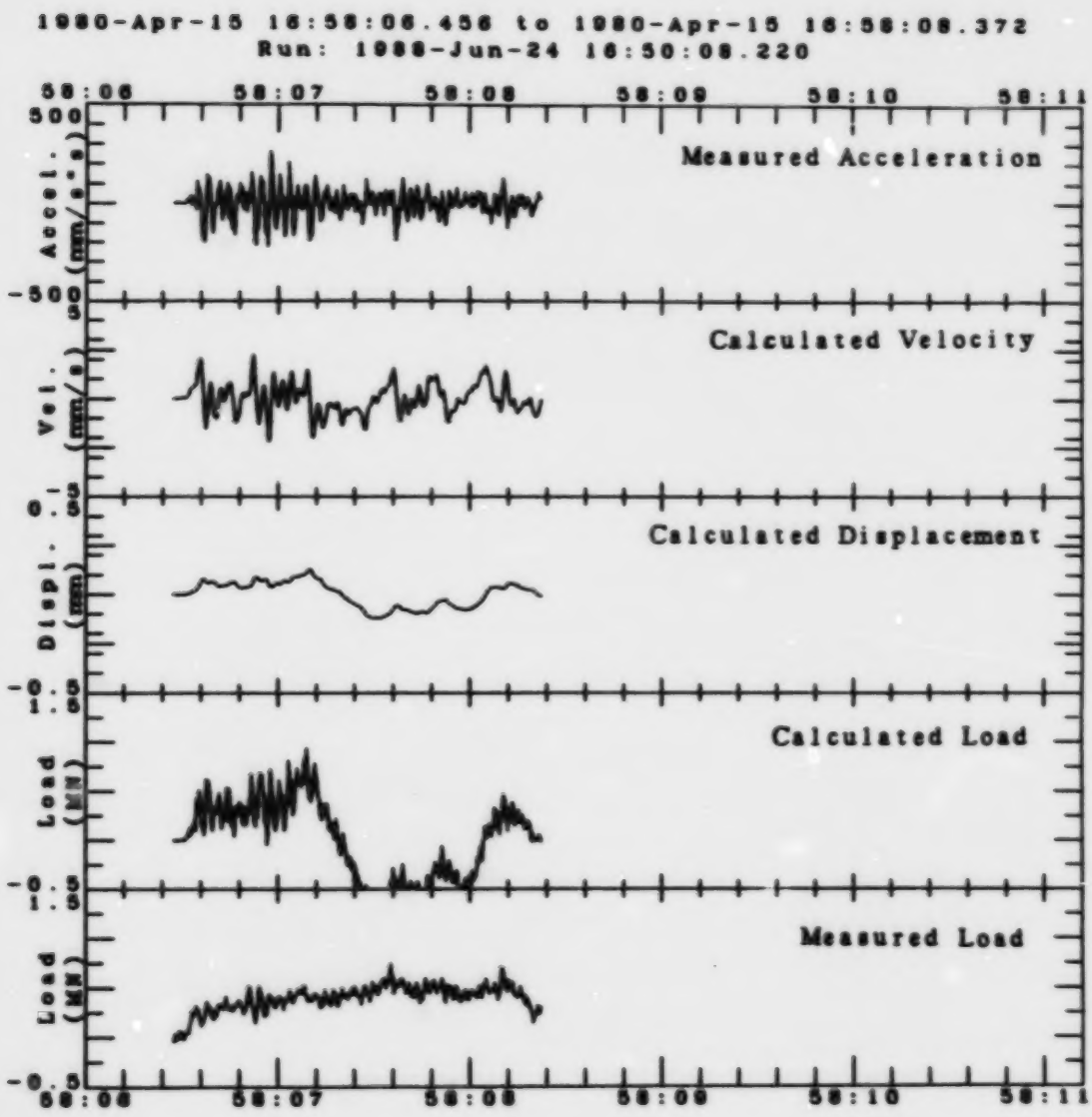

Figure 11 Comparison of the measured load history of event H80.04.15. 16.58.06 with the load history calculated from the measured acceleration history after baseline drift was removed using linear regression.

segment joints. For example, the errors produced by the discontinuities at the two segment joints in figure 12 were larger than the errors produced by the simple linear regression (figure 11).

Curvilinear regression using polynomial expansion was utilized to eliminate the connection errors produced by the segmented linear regression. The load history calculated after a curvilinear regression using a third order polynomial was applied to the acceleration data is shown in figure 13. Considerable error still exists in this calculated load history because the baseline was not determined accurately enough; and, when even higher order polynomials are used in the regression analysis, the calculated peaks tend to be reduced before the errors caused by baseline drift are eliminated.

The simple linear regression works as well or better than the other two regression techniques. There is no additional benefit to using the more complex schemes and the schemes require additional subjective input such as the number of segments or the degree of the polynomial. Other methods of reducing error, such as reducing the integration time step, must be used in conjunction with linear regression if more accurate results are to be obtained.

4.3 Data Precision

The precision of the data is determined when the data is digitized for computer analysis. The data was originally recorded as an analog signal on FM tape. When the data was input into the computer, this continuous analog signal was converted into discrete digital values. The precision of this digital data was determined by the size of the time and voltage increments used during the digitizing process.

4.3.1 Time Increment

More detail can be captured in the digital record when the time increment is reduced. For example, when a short section of event H80.04.15.16.58.06 was digitized using a time step of 4.0 milliseconds,

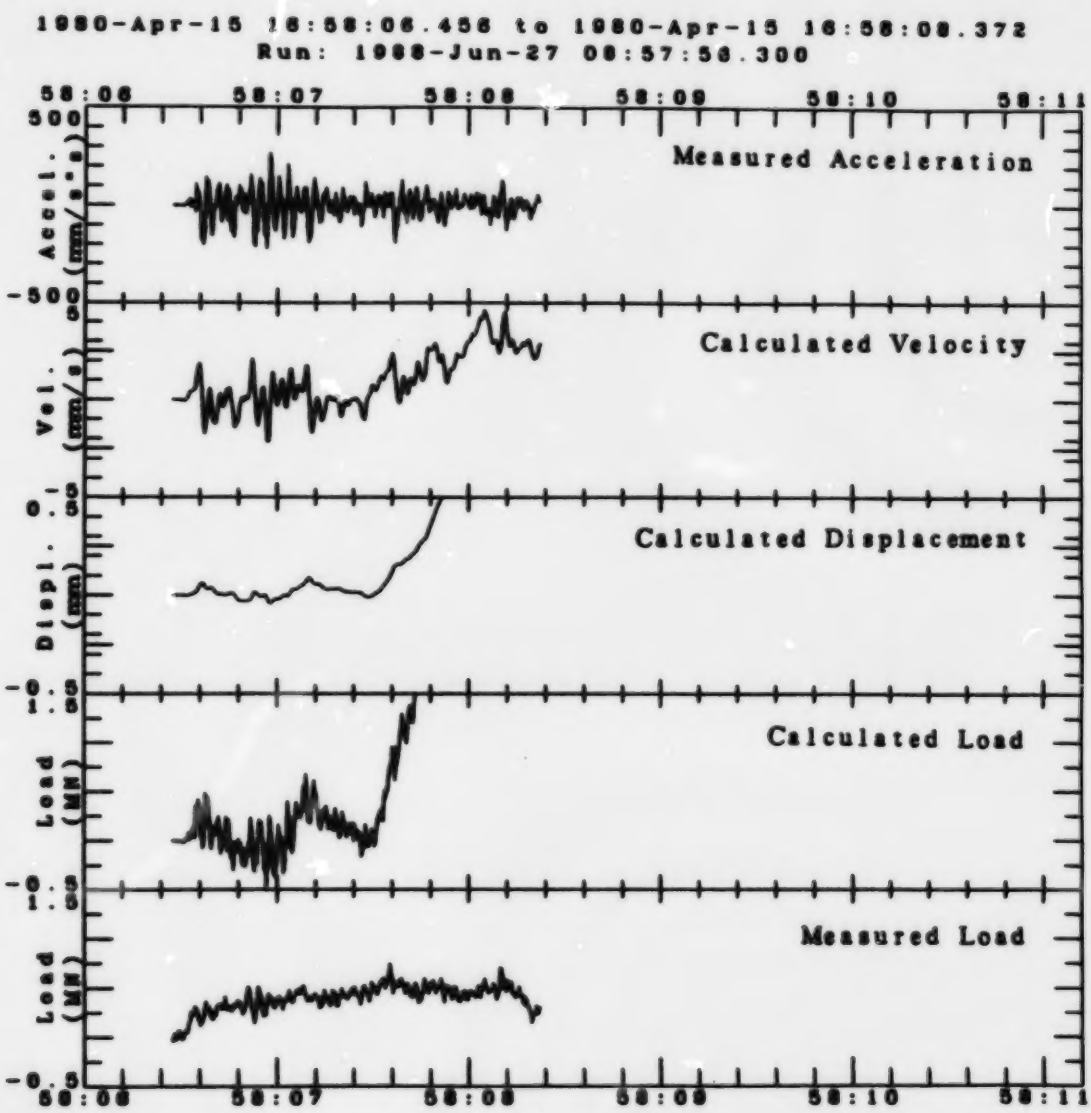

Figure 12 Comparison of the measured load history of event H80.04.15. 16.58.06 with the load history calculated from the measured acceleration history after baseline drift was removed using segmented linear regression with three segments.

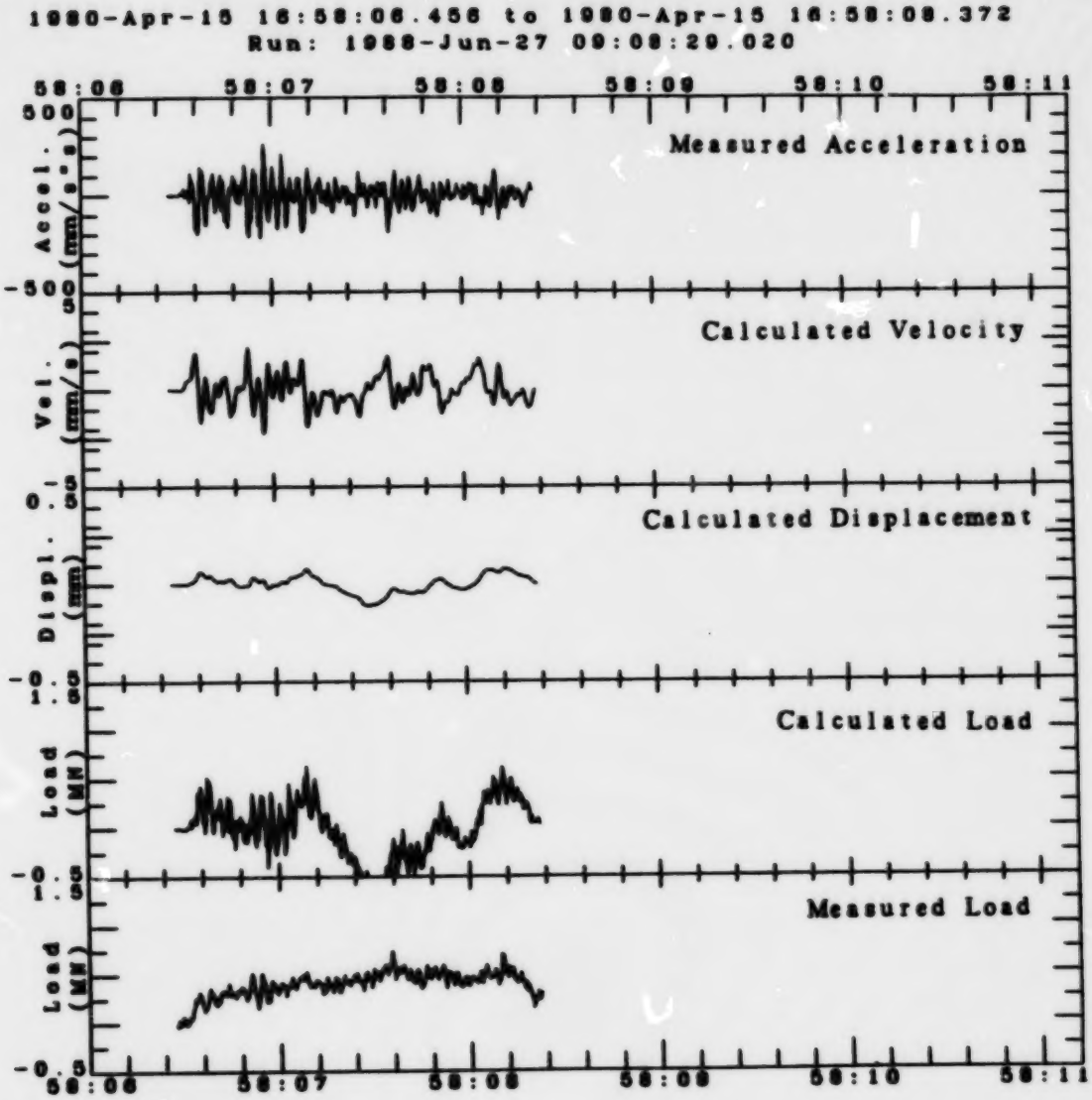

Figure 13 Comparison of the measured load history of event H80.04.15. 16.58.06 with the load history calculated from the measured acceleration history after baseline drift was removed using curvilinear regression with a third order polynomial.

only one relatively smooth acceleration cycle was produced; but, when the same section was digitized using a timestep of 1.0 milliseconds, much more detail was captured (compare figures 14 and 15). This increased detail should improve the results of integration.

To demonstrate that integration results improve when smaller time steps are used, the accelerations record from event H80.04.15.16.58.06 was digitized at three different time steps: 4.0, 1.0 and 0.5 milliseconds. The load history calculated from the acceleration data with the largest time step, 4.0 milliseconds, is shown in figure 11. Only the first part of this calculated load history was similar to the measured load history; the calculate load actually dropped below zero for part of the event. The accuracy of the calculated load history improved dramatically when acceleration data with a 1.0 millisecond time step was used in the analysis (figure 16). Although the magnitude of the calculated load history were slightly larger than those of the measured load history, the shape of the two load histories was quite similar. Further improvements in accuracy occurred when acceleration data with a 0.5 millisecond time step was used for the analysis, although these improvements were minor (figure 17). The use of even shorter time steps may improve the accuracy of integration even more, but, the number of data points required increases as well and this increases both the storage requirements and the processing time of the model.

The length of the time step cannot be reduced indiscriminately due to the data storage limits of the computer hardware. The computer used in the digitizing process is a PDP11/24 with a real time Laboratory Peripheral Accelerator (LPA) subsystem attached. The maximum number of data points that can be stored in this computer during one digitizing run is 19,120 points; therefore, if the time step is reduced, the maximum duration is reduced by a proportional amount. For example, if a time step of 1.0 milliseconds is used, the maximum duration that can be digitized is 19.12 seconds. However, if a time step of 0.5 milliseconds is used, the maximum duration is reduced proportionally to 9.56 seconds. During model testing, when the measured acceleration and load histories were digitized simultaneously, the maximum duration was reduced, because

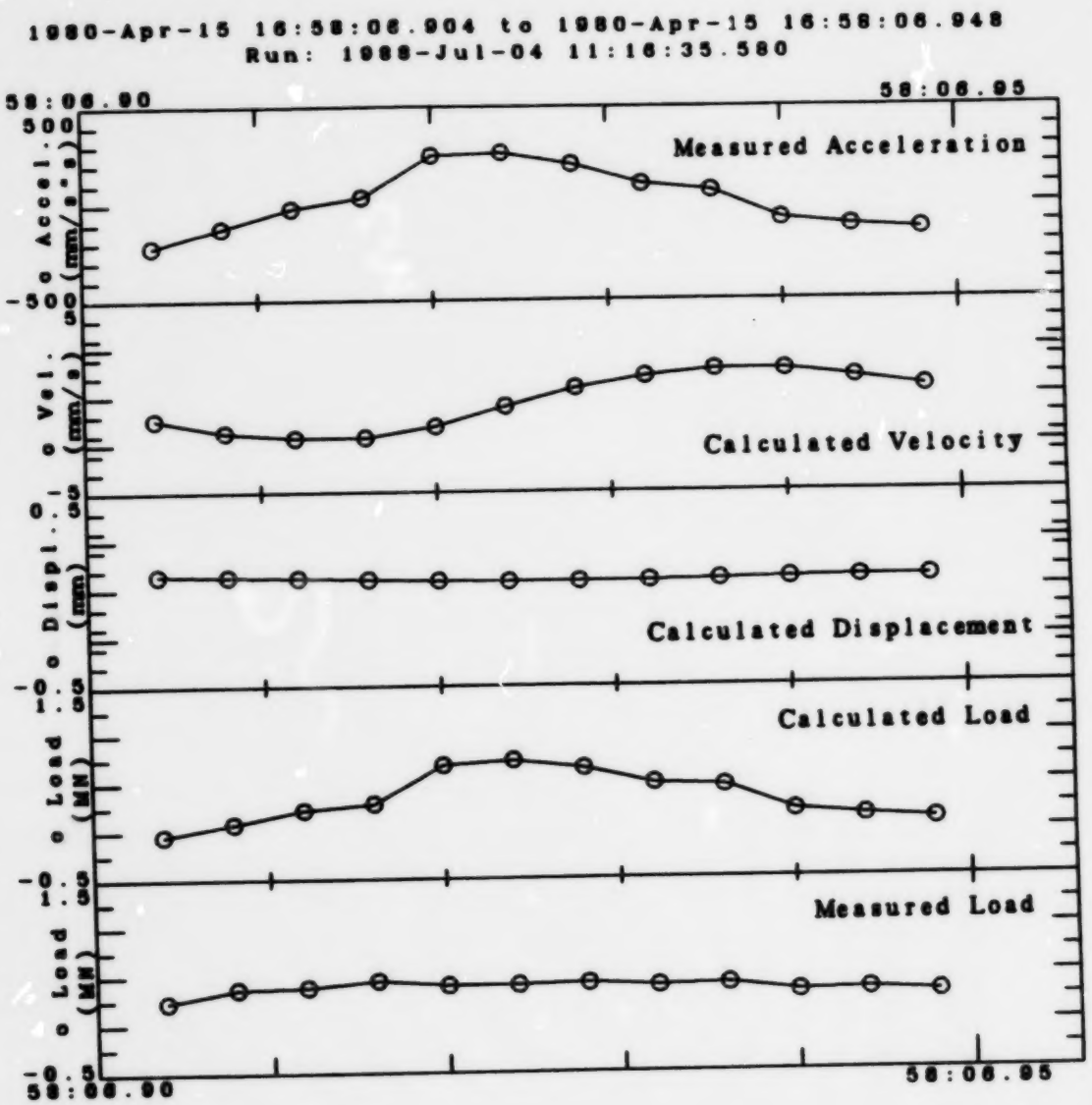

Figure 14 Expansion of a 50 millisecond segment of event H80.04.15.16.58.06 digitized with a timestep of 4.0 milliseconds.

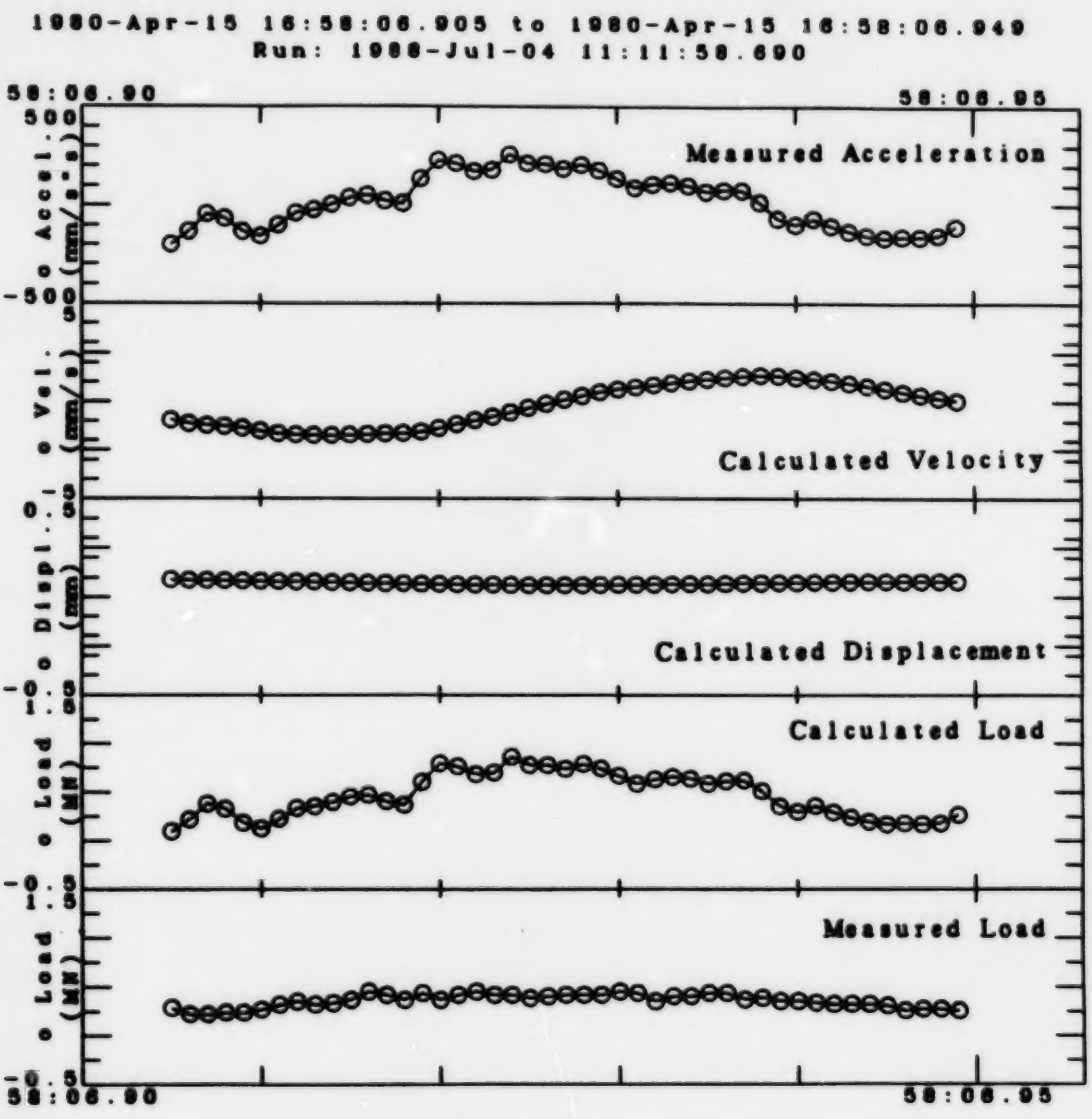

Figure 15 Expansion of a 50 millisecond segment of event H80.04.15.16. 58.06 digitized with a timestep of 1.0 milliseconds.

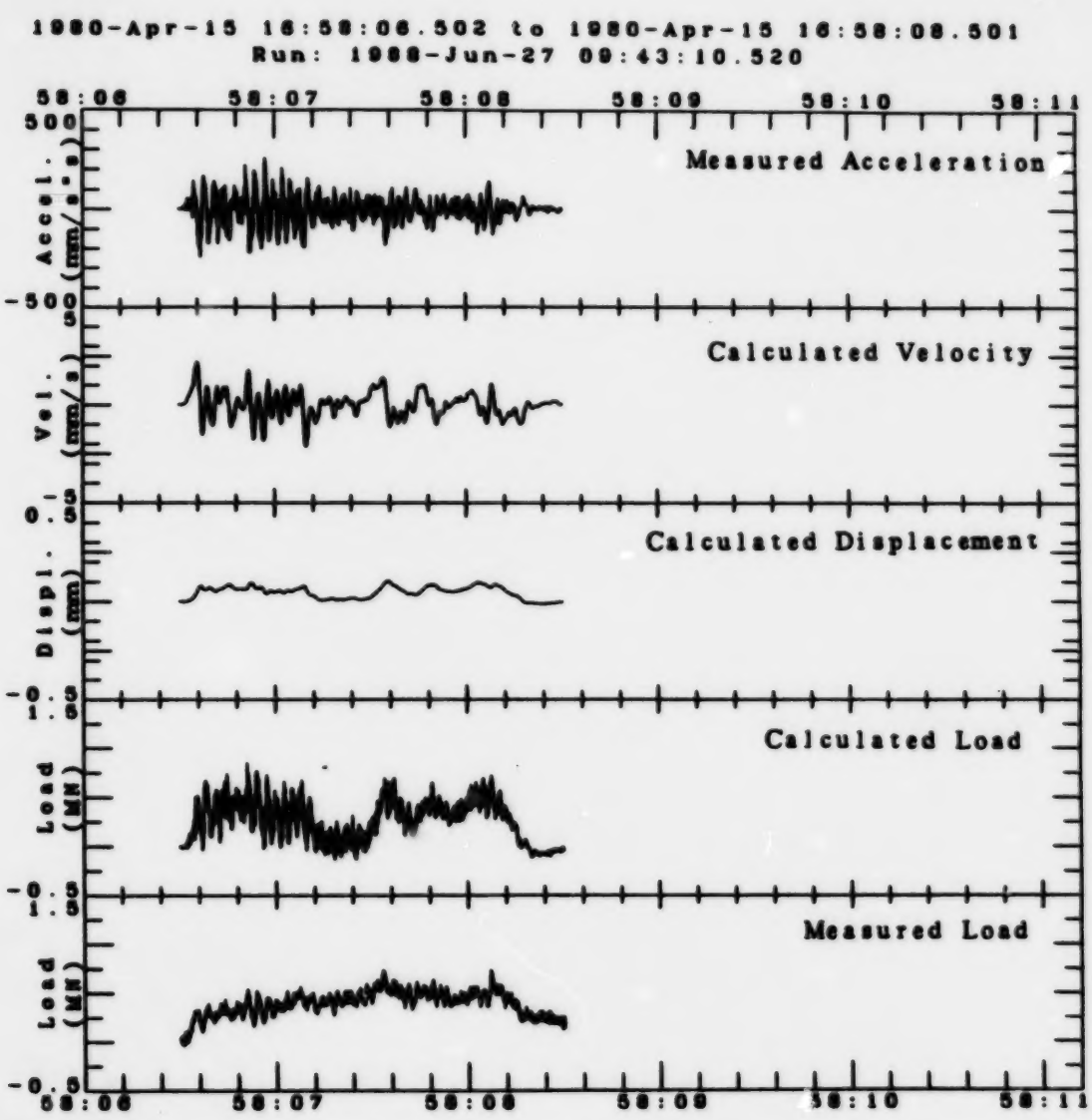

Figure 16 Comparison of the measured load history of event H80.04.15. 16.58.06 with the load history calculated from the measured acceleration history digitized using a time step of 1.0 milliseconds.

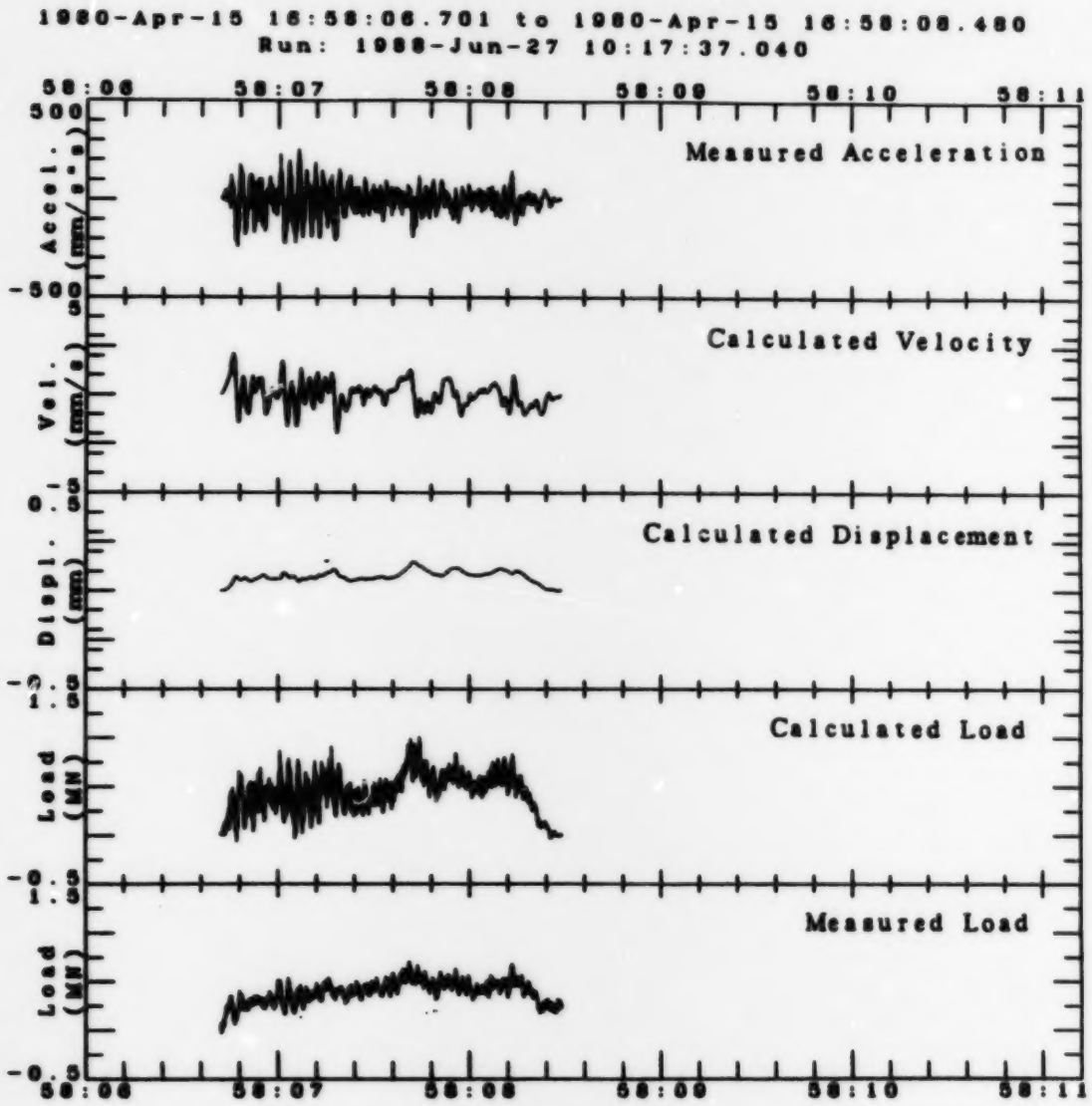

Figure 17 Comparison of the measured load history of event H80.04.15. 16.58.06 with the load history calculated from the measured acceleration history digitized using a time step of 0.5 milliseconds.

of the storage limitations, to half of what if would have been if only the acceleration history were digitized. Data digitized with time steps of less than 0.5 milliseconds could not be analyzed properly because the full events could not be digitized.

4.3.2 Voltage Increment

The computer hardware converts input voltage signals into integer values during the digitizing process. The largest integer available is 4096 which corresponds to an input voltage of +10 volts. The smallest integer, 0, corresponds to -10 volts. This produces a digitized voltage increment of 4.88 millivolts. This voltage increment was used when digitizing the data used in the examples in the previous section.

If increased precision is required, the input voltage signal can be amplified before it is digitized. Since voltages recorded an FM tape do not exceed 1.0 volts, the signal can be amplified by a factor of ten before it is fed into the computer. After the digitized data is divided by a factor of ten to eliminate the original amplification, the effective voltage increment becomes 0.488 milliseconds, one tenth of the original voltage increment. Event H80.04.15.16.58.06, the same event as used in previous examples, was redigitized with a time step of 1.0 milliseconds and an amplification factor of ten. The calculated load resulting from this data, shown in figure 18, appears similar to the calculated load produced from data digitized without amplification (figure 16). The increased digital precision does not appear to increase the accuracy of integration significantly.

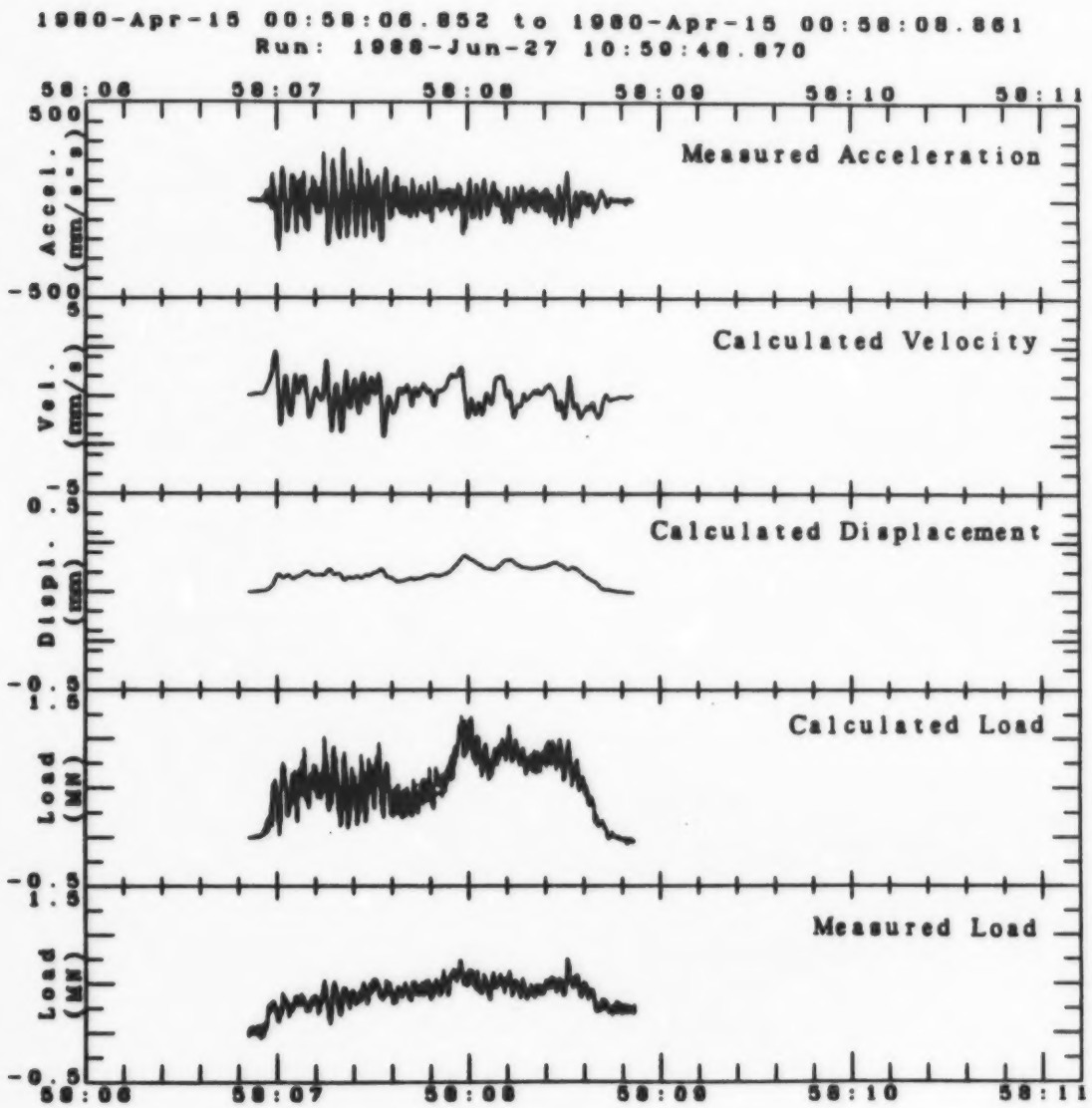

Figure 18 Comparison of the measured load history of event H80.04.15. 16.58.06 with the load history calculated from the measured acceleration history digitized using a time step of 1.0 milliseconds and an amplification factor of ten.

5.0 ANALYSIS

The numerical model was modified in an attempt to improve its ability to analyze long duration events accurately. Five events, with duration ranging from two seconds to five seconds, were selected for analysis. The accuracy of the model could then be evaluated by comparing the load histories generated from the acceleration data of these events with the load histories obtained from corresponding load cell data. Initial testing described in section 4.0 suggested that, from a numerical point of view and a data quality perspective, the optimal characteristics of the model given the available hardware were: trapezoidal numerical integration, linear regression for baseline determination, and a time step of 0.5 milliseconds. These optimal characteristics were used in the analysis of the five selected long duration events.

Two events with durations of about two seconds were analyzed using the new model. Both these events, H80.04.15.16.58.06 and H82.04.24.08.06.11, had been analyzed without success using the previous model (Van Der Vinne, 1988), although the previous model was only tested using a time step of 4.0 milliseconds. When event H80.04.15.16.58.06 was analyzed using the present model but still using a time step of 4.0 milliseconds (figure 11), the results were identical to the results obtained from the previous model. This suggests that the improved results obtained when using a 0.5 millisecond time step with the new model (figure 17) are a consequence of using the smaller time step rather than a product of the changes in the method of calculation. The calculated load history shown in figure 17 does not contain the negative loads that appeared in the calculated load history in figure 11; in fact, both the calculated and measured load histories in figure 17 exhibit the same general features although larger amplitude fluctuations were observed in the calculated load history. The calculated load history of event H82.04.24.08.06.11 (figure 19) is still greater in magnitude than the measured load history but not as great as when the previous model was used in the analysis. When the previous Fourier transform model was used in the analysis of this event, the calculated load history had a peak magnitude of 3.47 MN, almost three times the peak magnitude of the

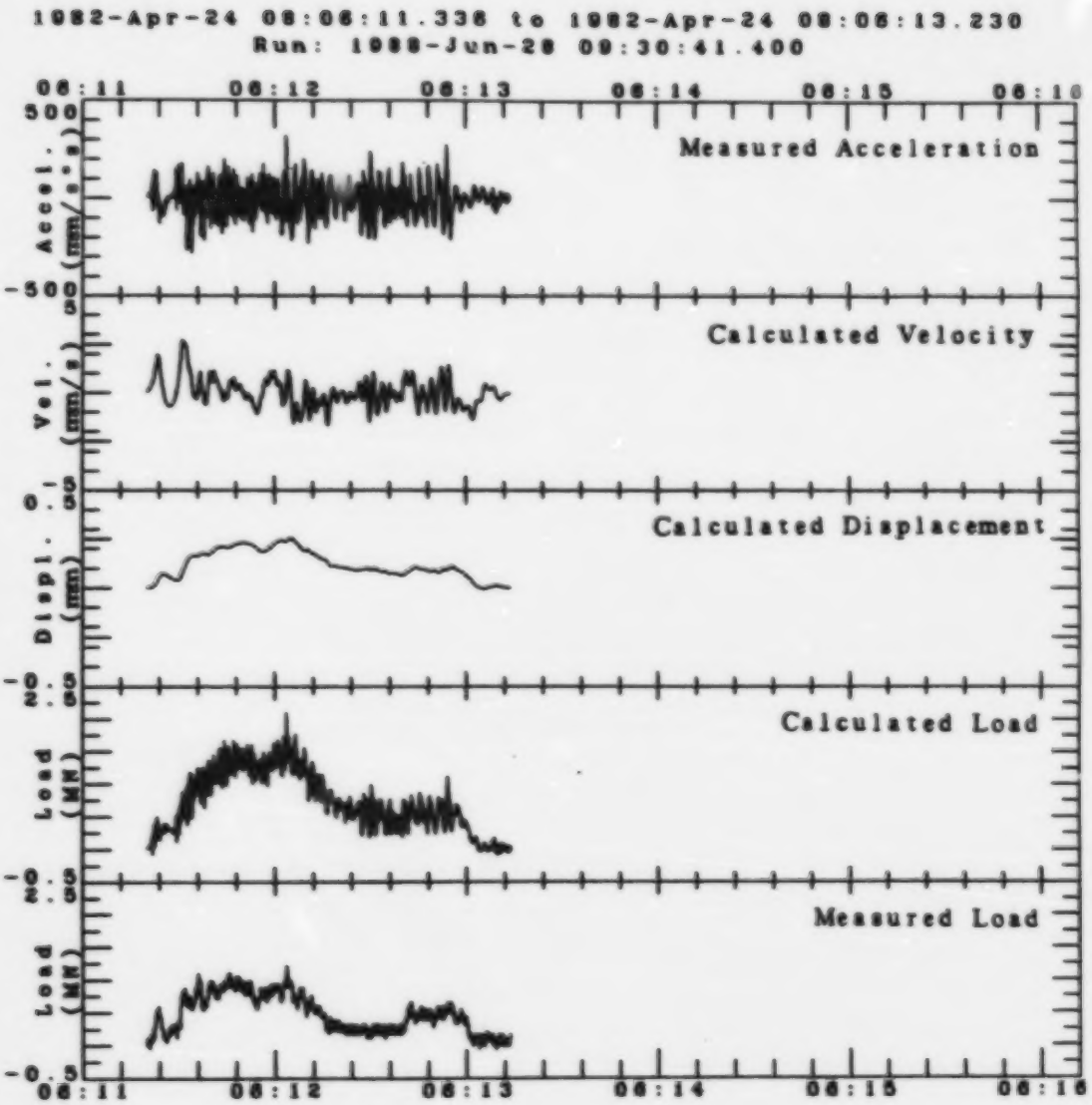

Figure 19 Comparison of the measured load history of event H82.04.24. 08.06.11 with the load history calculated form the measured acceleration history digitized using a time step of 0.5 milliseconds.

measured load history; but, when this same event was analyzed using the new double integration model, the peak magnitude of the calculated load history was reduced to 2.12 MN. This value is still large compared to the measured peak load, 1.21 MN, but it is a significant improvement over the results of the previous model. The shape of the calculated load history matches the shape of measured load history more closely as well, although there are some large fluctuations in the latter part of the calculated load history which obscure the shape of the second peak.

Since the model could adequately reproduce two second events, the analysis of longer duration loads was attempted as well. Event H82.04.24.00.48.14, which has a duration of three seconds, is shown in figure 20. The calculated load history of this event has the same general features as the measured load history although some minor differences in magnitude were evident. The results of the analysis of a four second event, event H82.04.24.08.05.15, were not as good (figure 21). Significant error occurred in the calculated load history, possibly caused by non-linear baseline drift. When accelerations from a five second event, event H82.04.24.00.50.02, were analyzed, the results were poor as well (figure 22). A significant portion of the calculated load history was below zero, a physical impossibility. The peak acceleration, which occurred approximately three seconds into the event, may be extraneous because there was no corresponding change in the measured load at this point. This extraneous acceleration may be caused by traffic on the bridge or vibrations transmitted through the bridge deck from an adjacent pier rather than being produced by a change in load. A large error in the acceleration history such as this will distort the model results significantly. The model worked well when analyzing events of three seconds duration or less but when events with longer durations were analyzed, serious errors occurred.

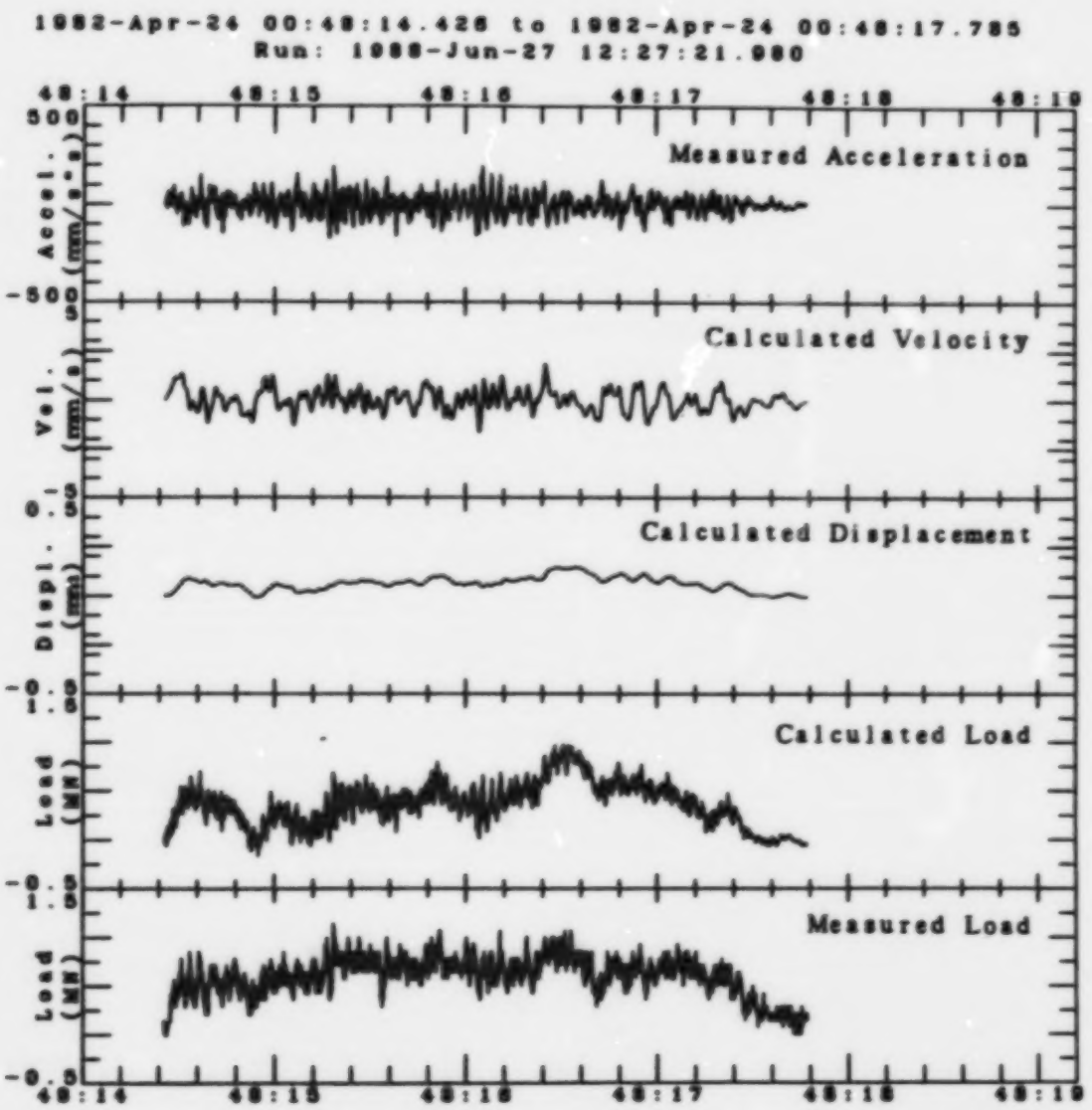

Figure 20 Comparison of the measured load history of event H82.04.24. 00.48.14 with the load history calculated from the measured acceleration history digitized using a time step of 0.5 milliseconds.

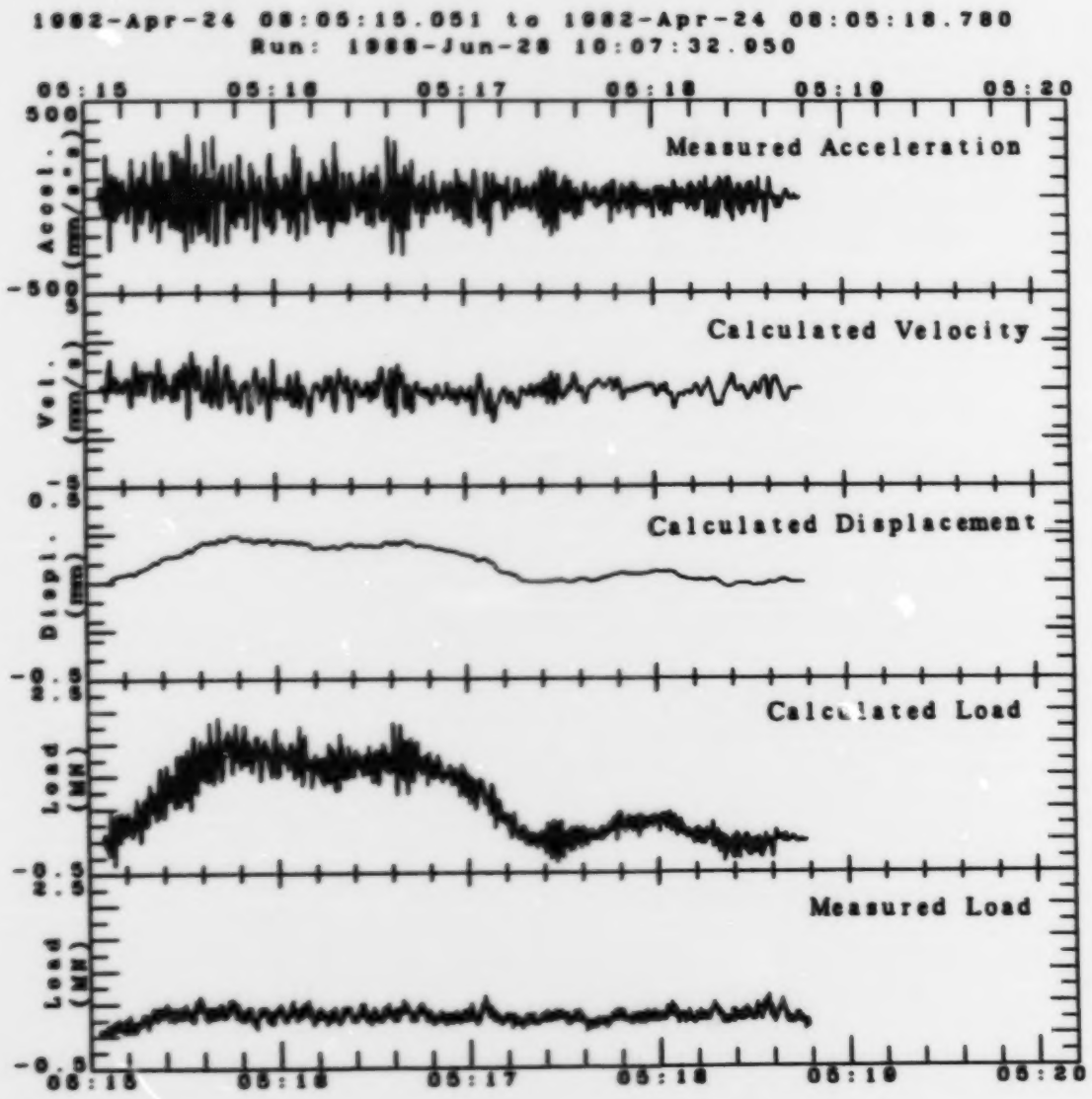

Figure 21 Comparison of the measured load history of event H82.04.24. 08.05.15 with the load history calculated from the measured acceleration history digitized using a time step of 0.5 milliseconds.

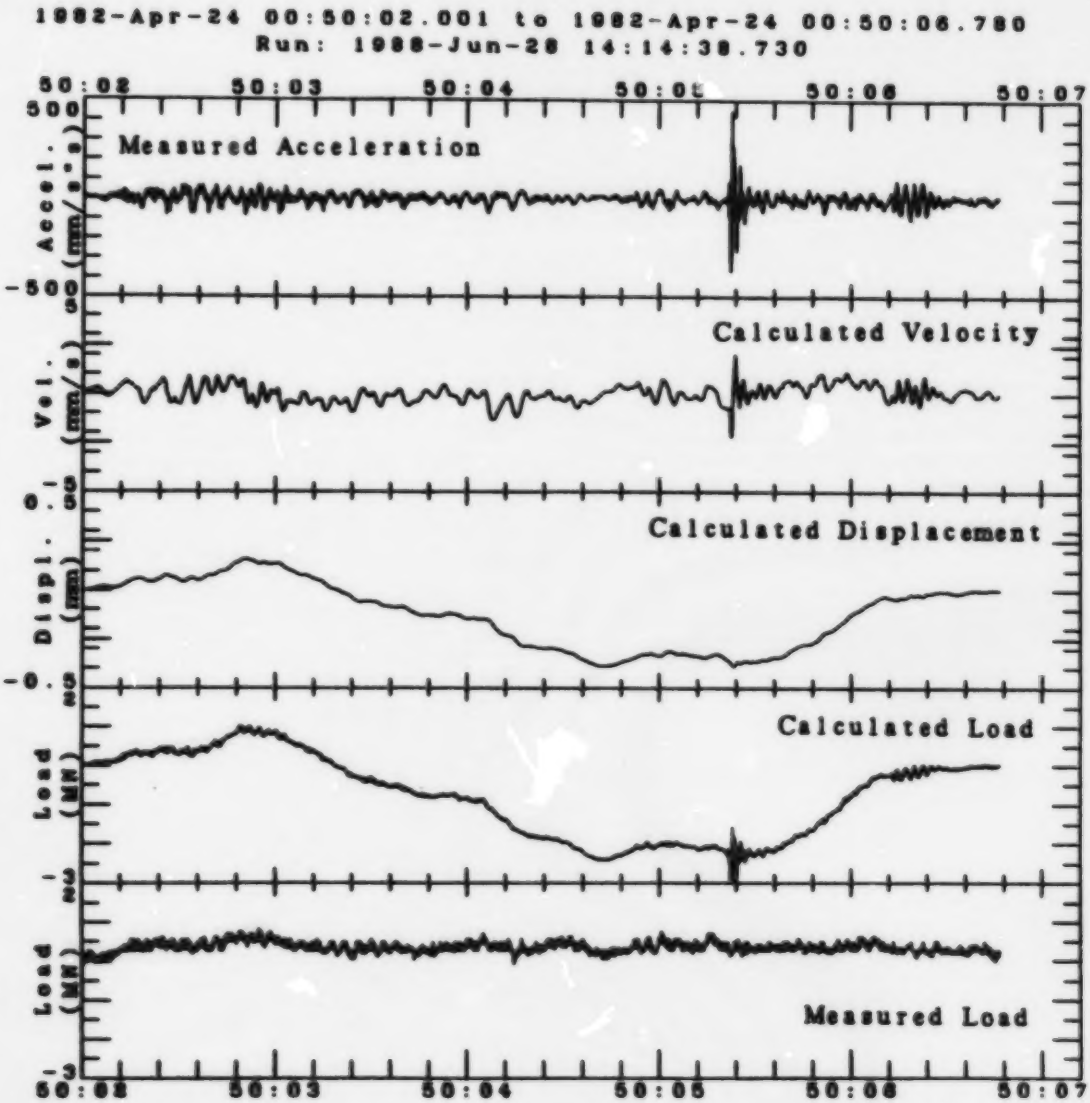

Figure 22 Comparison of the measured load history of event H82.04.24. 00.50.02 with the load history calculated from the measured acceleration history digitized using a time step of 0.5 milliseconds.

6.0 CONCLUSION AND RECOMMENDATIONS

Previous attempts to evaluate the suitability of using a single-degree-of-freedom numerical model of bridge pier vibration to convert acceleration measurements into ice load data found that load events with durations of less than one second could be calculated successfully. However, load events with longer durations could not be calculated without introducing serious errors. In an attempt to improve the model results for longer duration events, the Fourier transform solution technique of the original model was replaced with a numerical integration solution technique. This modified model was then refined and tested for reliability by comparing the ice load histories obtained by the model with those obtained from load cell measurements.

Initial testing of the new model suggested that from a numerical point of view the trapezoidal integration technique would produce the best results. A more accurate integration scheme was tested as well but the results were poor because smoothing of the acceleration data was required and this introduced additional error to the calculations. The best approximation of the acceleration baseline was the straight line obtained from linear regression of the acceleration data set. More complex regression schemes, such as segmented linear regression and curvilinear regression, were also tested in an attempt to determine the acceleration baseline more accurately, however, in most cases, more error occurred in the results after these techniques were applied.

The major advantage of using numerical integration in the model is that the significance of the time step becomes obvious. Numerical integration is much more accurate when smaller time steps are used. Improvements in the results of the new model were a direct result of reducing the time step of the acceleration data. When the time step was reduced form 4.0 milliseconds to 0.5 milliseconds, an improvement in digital precision of eight times, the event durations that could be analyzed accurately increased from less than one second to more than three seconds. Unfortunately, the size of the time step could not be reduced further due to system limitations, although, even if the time

step could be reduced further, it may not be possible to increase the accuracy of the model results. The model assumes that the pier vibrates solely as a single-degree-of-freedom system; therefore, if secondary modes of vibration occur in the acceleration record, they will produce errors in the model results no matter how small the time step becomes. However, it is not possible to test a multi-degree-of-freedom model because at least two sets of streamwise acceleration data are needed and they are not available for the Hondo bridge pier. Further improvements in the model results are unlikely, given the system constraints and the present data set.

Other massive piers have been instrumented to obtain acceleration records during ice runs. A large pier of the Highway 67 bridge over the Peace River near Fort Vermillion was instrumented during the 1981, 1983 and 1985 ice runs. Also, in 1985 and 1986, pier accelerations were obtained for the Highway 665 bridge over the Little Smoky River near Valleyview. There are no load cell measurements at these sites, so the severity of the events must be estimated from the acceleration data. Analysis of this data using the model will be of limited value because most of the major load events have durations greater than three seconds, and three seconds is the maximum duration that the model can handle successfully. Analysis of the short duration events at these sites would take approximately six months to complete; but, because the peak loads would not be established from this analysis, it is recommended that this analysis not be carried out.

The usefulness of this model is limited because of its inability to calculate loads with durations greater than three seconds, although the model could be used to calculate ice loads on small streams if short duration impact loads and splitting failures are dominant. Still, there is a risk that the peak load event will be too long for accurate analysis.

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APPENDIX A

Source Code for Numerical Model which Calculates Ice Forces from Pier Acceleration Data using Numerical Integration

```
C LOADDI.FOR (DOUBLE INTEGRATION METHOD)
C
C PROGRAM TO CALCULATE THE FORCE INPUT FROM THE ACCELERATION
C OUTPUT FOR A SDOF SYSTEM
C
C DOUBLE INTEGRATION ANALYSIS
C
C RUN COMMANDS
C     $ASSIGN LOAD.DAT FOR005
C     $ASSIGN OUTP.DAT FOR006
C     $ASSIGN A82E14.DAT FOR008
C     $ASSIGN L82E14.DAT FOR010
C     $FORTRAN LOAD                                    *THESE TWO COMMANDS ARE
C     $LINK LOAD,JANUS::SYS$LIBRARY:IMSLIBD/LIB  *ONLY USED IN COMPILING
C     $RUN LOAD
C
C NOTE: A TEXT FILE ARE OPENED WHEN THIS PROGRAM
C        IS RUN: TIME.TXT
C        THIS FILE CONTAINS THE DATA NEEDED FOR PLOTTING
C
C PLOT COMMANDS
C     $ADD AIR
C     $TXTtoADB (TIME.TXT )TIME.ADB
C     $TIMECHART (TIME.ADB )PLOTFILE=TIME.PDF
C     $GSPVIEW TIME.PDF
C          OR
C     $GSPPLOT/DEV=LPC TIME.PDF
C
C IMPORTANT VARIABLES
C
C ACCEL(20) = TITLE OF ACCELERATION DATAFILE
C COR = CORRELATION COEFFICIENT FROM LINEAR REGRESSION
C DATE(I) = DATE OF EVENT (1980-APR-15)
C DELT = TIME BETWEEN ACCEL. INPUT DATA POINTS
C DELTLC = TIME BETWEEN LOAD DATA POINTS, USUALLY SAME AS DELT
C FMT = FORMAT OF ACCELERATION INPUT DATA
C FMTLC = FORMAT OF LOAD INPUT DATA
C IHRS1(J) = FIRST DIGIT OF HOUR IN WHICH EVENT OCCURED
C IHRS2(J) = SECOND DIGIT OF HOUR
C IMOD = OPTION TO INDICATED WHETHER REGRESSION HAS FIXED ORIGIN
C      = 0 - NO FIXED ORIGIN
C      = 1 - FIXED ORIGIN
C
C KINT = OPTION TO ADD INTERVAL OF ZEROS TO THE BEGINNING OF
C        THE ACCELERATION DATA
C             = 0 (OR NEGATIVE) THEN LEAVE DATA AS IS
C             = N1 THEN N1 ZEROS ADDED TO BEGINNING OF DATA
C
C KLIN = OPTION TO REMOVE LINEAR TREND FROM DATA
C        KLIN = 0 (OR NEGATIVE OR >4) THEN LEAVE DATA AS IS
C             = 1 SUBTRACT LINEAR REGRESSIION LINE FROM DATA
C                  USING REGRESS SUBROUTINE
C             = 2 SUBTRACT CURVILINEAR TREND FROM DATA
C
C             = 3 SUBTRACT XOOMEAN FROM DATA
C
C KOUT(1-3) = 0 PRINT OUTPUT
C           = 1 SUPPRESS PRINTOUT
C           KOUT(1) = PRINTOUT OF ACCELERATION AND DISPLACEMENTS
C                (2) =            XOO, H, AND P IN FREQUENCY DOMAIN
C                (3) =            CALCULATED LOADS
```

```
C
C KSHIFT - SHIFT CALCULATED LOADS SUCH THAT INITIAL LOAD STARTS AT ZERO
C          (IE: P(1)=0.0)   KSHIFT=0 NO DON'T SHIFT
C                                   =1 YES SHIFT
C                                   =2 P(1)=XSUM/N - NO SHIFT
C
C KSTART - NUMBER OF DATA POINTS IGNORED AT START OF DATAFILE
C        - USED ONLY IF KLIN = 1,2,3
C        - MUST BE ZERO OR POSTIVE
C
C KFIN - NUMBER OF DATA POINTS IGNORED AT END OF DATAFILE
C      - USED ONLY IF KLIN = 1,2,3
C      - MUST BE ZERO OR POSITIVE
C
C KSTEP - OPTION TO LIMIT PLOTTING RESOLUTION
C       - MUST BE GREATER THAN ZERO
C       - KSTEP=1  PLOT ALL POINTS
C              =2  PLOT EVERY SECOND POINT
C              =3  PLOT EVERY THIRD POINT
C
C M = NUMBER OF DATA POINTS PER SEGMENT WHEN KLIN=1
C           OTHERWISE EQUAL TO NX
C MDP = ORDER OF POLYNOMIAL USED FOR CURVILINEAR REGRESSION
C MIN1(J) = FIRST DIGIT OF MINUTE FOR EVENT TIME
C MIN2(J) = SECOND DIGIT OF MINUTE
C N = NUMBER OF SEGMENTS USED FOR SEGMENTED REGRESSION
C
C NINT - OPTION TO CHOSE INTEGRATION SUBROUTINE
C      - MUST EQUAL 1 OR 2
C      - NINT = 1  USE INTEG SUBROUTINE (TRAPEZIOD INTEGRATION)
C             = 2  USE HAINT SUBROUTINE (HIGH ACCURACY INTEGRATION)
C
C NX = NUMBER OF ACCEL. INPUT DATA POINTS
C NXLC = NUMBER OF LOAD INPUT DATA POINTS
C P(J) = LOAD CALCULATED FROM ACCELERATION DATA
C PLC(J) = LOAD FROM LOAD CELL DATA
C PACCMAX = MAXIMUM FORCE VALUE TAKEN FROM CALCULATED LOAD HISTORY
C PLCMAX = MAXIMUM FORCE VALUE TAKEN FROM LOAD CELL DATA
C PLCLOW = BASELINE VALUE FOR LOAD CELL DATA BASED ON LOWEST 10 PT AVE.
C PLC10 = 10 POINT AVERAGE OF LOAD CELL LOADS
C RSQ = R-SQUARED LIMIT FOR CURVILINEAR REGRESSION
C     = USUALLY 100.0%
C S = STIFFNESS OF STRUCTURE
C SEC = SECOND WHEN EVENT STARTED (05.000)
C SLOPE = SLOPE OF BASELINE CORRECTION OF ACCELERATION DATA
C           IF KLIN = 1 SLOPE IS OBTAINED FROM LINEAR REGRESSION
C                   = 2 SLOPE INPUT VALUE IS USED
C SM = SMOOTHING FACTOR - VALUE DEPENDS ON SUM OF SQUARES OF DATA
C T(J) = TIME CORRESPONDING TO EACH INPUT POINT
C TITLE(I,J) = TITLE OF PLOTS
C TP = INPUT DURATION
C UNITS = UNITS OF ANALYSIS
C XI = DAMPING RATIO OF THE STRUCTURE
C XM = MASS OF THE STRUCTURE
C X(J) = DISPLACEMENT
C XO(J) = VELOCITY
C XOO(J) = ACCELERATION
C XOOMEAN = AVERAGE OF ACCELERATION DATA USED TO DEFINE ZERO VALUE
C             WHEN KLIN = 3
C YINT = Y-INTERCEPT OF LINEAR BASELINE CORRECTION
C           SAME OPTIONS AS SLOPE
```

```
C
C MAIN PROGRAM
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*4 ACCEL(20),UNITS(20),FMT(20),T(15120),
     1 TITLE(20,10),DATE(3)
     2 ,PLC(15120),FMTLC(20)
      REAL*8 X(15120),XO(15120),XOO(15120),P(15120),SM
      INTEGER IWK(15), IHRS1(15120),IHRS2(15200),
     * MIN1(15120),MIN2(15120)
      INTEGER  NINT, KLIN, KOUT(3), KSHIFT, KINT, KSTART, KFIN
C      COMMON WK(56014)
      LOGICAL*1 XFLAG
C CONSTANTS
      PI=3.141592653589793
C READ IN THE PROGRAM OPTIONS
      READ(5,1005)  KLIN, KSTEP, NINT, KOUT, KSHIFT, KINT, KSTART, KFIN
      WRITE(6,1006) KLIN,KSTEP, NINT,KOUT,KSHIFT,KINT, KSTART, KFIN
C READ IN VALUES TO MANIPULATE THE DATA
      READ(5,1091) MDP, RSQ, SM
      WRITE(6,1100) MDP, RSQ, SM
C INPUT STRUCTURAL CHARACTERISTICS
      READ(5,1000) XM,S,XI
      WRITE(6,1010)
      WRITE(6,1020) XM,S,XI
      READ(5,1030) M
C ACCELERATION AND LOAD DATA
C TITLE
      READ(8,1050) ACCEL
      WRITE(6,1060) ACCEL
C READ UNITS USED IN ANALYSIS
      READ(8,1050) UNITS
      WRITE(6,1060) UNITS
C READ DATE AND TIME
      READ(8,1051)(DATE(I),I=1,3)
      READ(8,1052)IHRS1(0),IHRS2(0),MIN1(0),MIN2(0),SEC
      WRITE(6,1061)(DATE(I),I=1,3),IHRS1(0),IHRS2(0),MIN1(0),MIN2(0),SEC
 1051 FORMAT(3A4)
 1052 FORMAT(4I1,F6.3)
 1061 FORMAT(1X,'DATE AND TIME OF EVENT'/6X,3A4,2I1,':',2I1,':',F6.3)
C READ FORMAT OF DATA
      READ(8,1050) FMT
      READ(10,1050) FMTLC
      WRITE(6,1060) FMT
C READ NUMBER OF INPUT DATA POINTS
      READ(8,1030) NX
      READ(10,1030) NXLC
      WRITE(6,1040) NX
C READ TIME BETWEEN DATA POINTS
      READ(8,1090) DELT
      READ(10,1090) DELTLC
      WRITE(6,1020) DELT
C CALCULATE THE INPUT DURATION
      XN=DFLOAT(N)
      TP=XN*DELT
C READ ACCELERATION HISTORY
      READ(8,FMT)(XOO(J),J=1,NX)
C READ LOAD HISTORY (LOAD CELL DATA)
      READ(10,FMTLC)(PLC(J),J=1,NXLC)
C SHIFT LOAD CELL DATA USING A TEN POINT MEAN AS ZERO
      PLCLOW=0.0
```

```
      DO 212 I=1,10
       PLCLOW=PLC(KSTART-KINT+I-1)+PLCLOW
  212 CONTINUE
      PLCLOW=PLCLOW/10.0
      DO 210 J=KSTART-KINT+1,NXLC-KFIN
       PLC10=0.0
       DO 211 I=1,10
        PLC10=PLC(J+I-1)+PLC10
  211  CONTINUE
       PLC10=PLC10/10.0
       IF(PLC10.LT.PLCLOW)PLCLOW=PLC10
  210 CONTINUE
      DO 220 J=KSTART-KINT,NXLC
      PLC(J)=PLC(J)-PLCLOW
  220 CONTINUE
C WRITE STRUCTURAL AND ACCELERATION DATA
      WRITE(6,1110)
      WRITE(6,1120)
      WRITE(6,1130) XM
      WRITE(6,1140) S
      WRITE(6,1150) XI
      WRITE(6,1160)
      WRITE(6,1170) ACCEL
      WRITE(6,1170) UNITS
      WRITE(6,1180) NX
      WRITE(6,1190) DELT
C   IGNORE FIRST KSTART AND LAST KFIN VALUE
C    USE X(J) AS TEMPORARY STORAGE OF NEW NX DATASET
       DO 17 J=KSTART+1,NX-KFIN
       X(J-KSTART)=XOO(J)
   17  CONTINUE
C SET NX TO ACTUAL NUMBER OF DATA POINTS USED
       NX=NX-KSTART-KFIN
C COMPLETE TRANSFER WITHOUT ALTERING DATA
      IF(KLIN.GT.3.OR.KLIN.LT.1)THEN
       DO 64 J=1,NX
        XOO(J)=X(J)
   64  CONTINUE
      ENDIF
      GO TO (61,62,63),KLIN
      WRITE(6,1257)
 1257 FORMAT(' NO LINEAR TREND REMOVED FROM DATA')
      GO TO 42
C REMOVE LINEAR TREND FROM ACCELERATIONS IF KLIN = 1
C IF M=NX SIMPLE LINEAR REGRESSION IS PERFORMED
C IF M<NX SEGMENTED LINEAR REGRESSION IS PERFORMED
   61 CONTINUE
      N=NX/M+1
      IMOD=0
      MM=0
      DO 20 K=1,N
      IF(MM+M.GT.NX)M=NX-MM
      DO 30 J=MM+1,MM+M
      XO(J-MM)=X(J)
   30  CONTINUE
      CALL REGRESS(DELT,XO,M,SLOPE,YINT,COR,XEND,IMOD)
      IMOD=1
      WRITE(6, 37) M, SLOPE, YINT, COR
   37 FORMAT(/' LINEAR TREND REMOVED FROM DATA,   NX=',I5/
     *' EQUATION OF LINE IS   Y = ',E12.5,'*(t) + ',E12.5/
     *' WITH A CORRELATION COEFFICIENT (r) =',F6.4/)
```

```
      DO 16 J=1,M
      XOO(J+MM)=XO(J)
   16 CONTINUE
      MM=MM+M
      IF(MM.GE.NX)GO TO 24
      DO 18 J=MM+1,NX
      X(J)=X(J)-XEND
   18 CONTINUE
   20 CONTINUE
   24 CONTINUE
C      IMOD=0
C      CALL REGRESS(DELT,XOO,NX,SLOPE,YINT,COR,XEND,IMOD)
C      WRITE(6, 37) NX, SLOPE, YINT, COR
      GO TO 42
C REMOVE CURVILINEAR TREND FROM DATA USING POLYNOMIAL
C  EXPANSION
   62 CONTINUE
      CALL CREGRESS(X,NX,DELT,RSQ,MDP)
      DO 71 J=1,NX
      XOO(J)=X(J)
   71 CONTINUE
      GO TO 42
C SUBTRACT XOOMEAN FROM THE DATASET
   63 CONTINUE
      XOOMEAN=0.0D0
      DO 19 J=1,NX
   19 XOOMEAN=XOOMEAN+X(J)
      XN=DFLOAT(NX)
      XOOMEAN=XOOMEAN/XN
      WRITE(6,1290)XOOMEAN
 1290 FORMAT(' XOOMEAN =',E12.6)
      DO 39 J=1,NX
   39 XOO(J) = X(J) - XOOMEAN
   42 CONTINUE
C ADD INTERVAL OF ZEROS TO BEGINNING OF
C ACCELERATION INPUT
      IF(KINT.LE.0) GO TO 21
      DO 22 J=1,NX
      I=NX+1-J
      XOO(I+KINT)=XOO(I)
 22   CONTINUE
      DO 23 J=1,KINT
      XOO(J)=0.0
 23   CONTINUE
      NX=NX+KINT
 21   CONTINUE
C SMOOTH THE DATA USING CUBIC SPLINE
C
C   ***DISABLED***
C
      IF(SM.GE.0.00)THEN
C      CALL SMOOTH(XOO,NX,DELT,SM)
      ENDIF
C CALCULATE THE TIME-CORRESPONDING TO EACH INPUT POINT
C  WARNING! THIS TIME CALCULATION DOES NOT INCREMENT DAYS!
      DO 40 J=1,NX
       MIN2(J)=MIN2(0)
       MIN1(J)=MIN1(0)
       IHRS2(J)=IHRS2(0)
       IHRS1(J)=IHRS1(0)
       T(J)=DFLOAT(J+KSTART-KINT)*DELT+SEC
```

```
        IF(T(J).GE.60.000)THEN
          INC=INT(T(J)/60.000+0.00005)
          MIN2(J)=MIN2(J)+INC
          T(J)=T(J)-FLOAT(INC*60)
          IF(MIN2(J).GE.10)THEN
            MINC2=MIN2(J)/10
            MIN2(J)=MIN2(J)-MINC2*10
            MIN1(J)=MIN1(J)+MINC2
            IF(MIN1(J).GE.6)THEN
              MINC1=MIN1(J)/6
              MIN1(J)=MIN1(J)-MINC1*6
              IHRS2(J)=IHRS2(J)+MINC1
              IF(IHRS2(J).GE.10)THEN
                IHRS2(J)=IHRS2(J)-10
                IHRS1(J)=IHRS1(J)+1
              ENDIF
            ENDIF
          ENDIF
        ENDIF
   40 CONTINUE
C CALCULATE THE VELOCITY HISTORY
      IF(NINT.EQ.1)THEN
       CALL INTEG(XOO,NX,NX,DELT,XO)
      ELSE
C
C  ***DISABLED***
C
C       CALL HAINT(DELT,XOO,XO,NX)
      ENDIF
C      IF(KLIN.EQ.2)THEN
C       IMOD=0
C       CALL REGRESS(DELT,XO,NX,SLOPE,YINT,COR,XEND,IMOD)
C      WRITE(6, 37) NX, SLOPE, YINT, COR
C      ENDIF
      IF(NINT.EQ.1)THEN
      CALL INTEG(XO,NX,NX,DELT,X)
      ELSE
C
C   ***DISABLED***
C
C      CALL HAINT(DELT,XO,X,NX)
      ENDIF
C ALSO WRITE THE ACCELERATION, VELOCITY AND DISPLACEMENT HISTORIES
      IF(KOUT(1).EQ.1) GO TO 54
      WRITE(6,1200)
      WRITE(6,1210)
      DO 53 J=1,NX
       WRITE(6,1220) J,T(J),XOO(J),XO(J),X(J)
   53 CONTINUE
   54 CONTINUE
C
C LOADS CALCULATED BY SUMMING TERMS IN DIFFERENTIAL EQUATION
C       P(J) = XM*XOO(J) + XC*XO(J) + S*X(J)
C
      XC=2*XI*DSQRT(XM*S)
      DO 55 J=1,NX
        P(J) = XM*XOO(J) + XC*XO(J) + S*X(J)
   55  CONTINUE
C WRITE AND PLOT THE FORCE HISTORY
C IF KSHIFT = 1 THEN SHIFT THE LOADS SO THAT P(1) = 0.0
      IF(KSHIFT.NE.1) GO TO 98
```

```
      CONST = P(1)
      DO 97 J=1,NX
   97 P(J)=P(J)-CONST
   98 CONTINUE
      IF(KOUT(3).EQ.1) GO TO 99
      WRITE(6,1260)
      WRITE(6,1270)
   99 DO 100 J=1,NX
       IF(KOUT(3).NE.1) WRITE(6,1250) J,T(J),P(J)
  100 CONTINUE
C FIND AND WRITE PEAK FORCE VALUES
      PLCMAX=0.0D0
      PACCMAX=0.0
      DO 250 J=1,NX
       IF(P(J).GT.PACCMAX)THEN
        PACCMAX=P(J)
        TACCMAX=T(J)
       ENDIF
       IF(PLC(J+KSTART-KINT).GT.PLCMAX)THEN
        PLCMAX=PLC(J+KSTART-KINT)
        TLCMAX=T(J)
       ENDIF
  250 CONTINUE
C FIND AND WRITE PEAK ACCEL. MAGNITUDE
      XOOMAX=0.0D0
      DO 251 J=1,NX
       IF(DABS(XOO(J)).GT.XOOMAX)THEN
        XOOMAX=DABS(XOO(J))
        TOOMAX=T(J)
       ENDIF
  251 CONTINUE
      WRITE(6,1303)XOOMAX,TOOMAX
 1303 FORMAT(/' MAXIMUM ACCELERATION MAGNITUDE:'/
     *'   XOO=',F8.2,'mm/s*s  AT TIME:',F6.3)
      WRITE(6,1301)PACCMAX,TACCMAX
 1301 FORMAT(/' MAXIMUM FORCE OBTAINED FROM ANALYSIS'/
     *'  OF ACCELERATION DATA:'/
     *'     F=',F8.4,'MN   AT TIME:',F6.3)
      WRITE(6,1302)PLCMAX,TLCMAX
 1302 FORMAT(/' MAXIMUM FORCE OBTAINED FROM THE'/
     *'  LOAD CELL DATA:'/
     *'     F='F8.4,'MN    AT TIME:',F6.3)
C
C  OPEN TEXT FILE FOR PLOT DATA
C
      OPEN (UNIT=11, STATUS='NEW', CARRIAGECONTROL='LIST',
     *FILE='TIME.TXT')
C
      WRITE(11,1253)
 1253 FORMAT(1X,'TAGS 331 340 332 333 334')
      DO 103 J=1,NX,KSTEP
      IF(T(J).LT.10.000)THEN
      WRITE(11,1251)(DATE(I),I=1,3),IHRS1(J),IHRS2(J),MIN1(J),MIN2(J),
     *T(J),XOO(J),XO(J),X(J),P(J),PLC(J+KSTART-KINT)
      ELSE
      WRITE(11,1252)(DATE(I),I=1,3),IHRS1(J),IHRS2(J),MIN1(J),MIN2(J),
     *T(J),XOO(J),XO(J),X(J),P(J),PLC(J+KSTART-KINT)
      ENDIF
 1251 FORMAT(1X,'DATA ',3A4,2I1,':',2I1,':0',F5.3,1X,
     *E10.4,1X,E10.4,1X,E10.4,1X,E10.4,1X,E10.4)
 1252 FORMAT(1X,'DATA ',3A4,2I1,':',2I1,':',F6.3,1X,
```

```
     *E10.4,1X,E10.4,1X,E10.4,1X,E10.4,1X,E10.4)
  103  CONTINUE
C
      CLOSE (UNIT=11, STATUS='KEEP')
C
 1000 FORMAT(3E12.6)
 1005 FORMAT(I4,I4,I1,3I1,I1,3I4)
 1006 FORMAT(' KLIN  =',I4/
     1' KSTEP=',I4/' KACC  =',I1/
     2' KOUT  =',3(I1,',')/' KSHIFT=',I1/' KINT  =',I4/
     3' KSTART =',I4/' KFIN =',I4/)
 1010 FORMAT(' ','INPUT DATA'/)
 1020 FORMAT(' ',3E12.6)
 1030 FORMAT(I5)
 1040 FORMAT(' ',I5)
 1050 FORMAT(20A4)
 1060 FORMAT(' ',20A4)
 1070 FORMAT(6E12.6)
 1080 FORMAT(' ',6E12.6)
 1090 FORMAT(3E12.6)
 1091 FORMAT(I5,2E12.6)
 1100 FORMAT(/' MAX DEGREE     = ',I5/' MAX VARIATION (%)  =',E12.6
     */' SMOOTHING FACTOR =',E12.6)
 1110 FORMAT(' ',/,'ANALYSIS IN THE FREQUENCY DOMAIN'/)
 1120 FORMAT(' ','STRUCTURAL CHARACTERISTICS'/)
 1130 FORMAT(' ',10X,'MASS=',2X,1PE12.4)
 1140 FORMAT(' ',10X,'STIFFNESS=',2X,1PE12.4)
 1150 FORMAT(' ',10X,'DAMPING RATIO=',2X,1PE12.4,/)
 1160 FORMAT(' ','ACCELERATION DATA'/)
 1170 FORMAT(' ',10X,20A4)
 1180 FORMAT(' ',10X,'NUMBER OF DATA POINTS=',2X,I5)
 1190 FORMAT(' ',10X,'TIME BETWEEN DATA POINTS=',2X,1PE12.4,/)
 1200 FORMAT(' ',/,'ACCELERATION AND DISPLACEMENT HISTORIES'/)
 1210 FORMAT(' ',10X,'J',6X,'TIME',10X,'ACCELERATION',2X,
     1 'DISPLACEMENT')
 1220 FORMAT(' ',10X,I5,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4)
 1230 FORMAT(' ',/,'QUANTITIES IN THE FREQUENCY DOMAIN'/)
 1240 FORMAT(' ',10X,'J',6X,'FREQUENCY',5X,'RE(CX00)',6X,'IM(CX00)',6X,
     1 'RE(H)',9X,'IM(H)',9X,'RE(P)',9X,'IM(P)')
 1250 FORMAT(' ',10X,I5,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4,
     1 2X,1PE12.4,2X,1PE12.4,2X,1PE12.4)
 1260 FORMAT(' ',/,'FORCE HISTORY'/)
 1270 FORMAT(' ',10X,'J',6X,'TIME',10X,'RE(P)',9X,'IM(P)')
      STOP
      END
C
C
C INTEG
C
C SUBROUTINE TO CALCULATE THE DISPLACEMENT HISTORY FROM THE
C ACCELERATION HISTORY
C
      SUBROUTINE INTEG(XO,NX,N,DELT,X)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION X(15120),XO(15120)
C CALCULATE THE DISPLACEMENT HISTORY ASSUMING A LINEAR VARIATION OF
C ACCELERATION OVER SMALL INCREMENTS OF TIME
      X(1)=0.0D0
      DO 10 J=2,NX
       X(J)=X(J-1)+XO(J-1)*DELT+(XO(J)-XO(J-1))*DELT/2.0D0
   10 CONTINUE
```

```
C ADD AN INTERVAL OF ZERO INPUT AT THE END OF THE DISPLACEMENT
C HISTORY
      IF(NX.EQ.N) GO TO 40
      NDUM=NX+1
      DO 30 J=NDUM,N
       X(J)=0.0D0
   30 CONTINUE
   40 CONTINUE
      RETURN
      END
C
C REGRESS
C
C  LINEAR REGRESSION OF DATA SET TO REMOVE LINEAR TREND
C  FROM DATA.
C
      SUBROUTINE REGRESS(DELT,X,N,A,B,COR,C,IMOD)
C
      REAL*8 T(15120),X(15120),XY(15120,2),PRED(15120,7)
      REAL*8 ALBAP(3),DES(5),ANOVA(14),STAT(9)
      DATA ALBAP/0.05,0.10,0.01/
C
      DO 10 J=1,N
      T(J)=DFLOAT(J-1)*DELT
      XY(J,1)=T(J)
      XY(J,2)=X(J)
      PRED(J,1)=T(J)
   10 CONTINUE
C
      CALL RLONE(XY,15120,N,IMOD,1,ALBAP,DES,
     * ANOVA,STAT,PRED,15120,N,IER)
C
C  SUBTRACT LINEAR DRIFT FROM DATA
C
      DO 20 J=1,N
      X(J)=X(J)-PRED(J,2)
   20 CONTINUE
C
C  CALCULATE CONSTANTS FOR EQUATION: X = A*T + B
C
      A=(PRED(N,2)-PRED(1,2))/(T(N)-T(1))
      B=PRED(N,2)-A*T(N)
      C=PRED(N,2)
      COR=DES(5)
      RETURN
      END
C
C CREGRESS
C
C POLYNOMIAL EXPANSION USED TO REMOVE CURVILINEAR TREND
C  FROM DATA
C
      SUBROUTINE CREGRESS(X,N,DELT,RSQ,MDP1)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION MDP(3)
      REAL*8 T(8192),X(8192),XYW(8192,13),PRED(8192,6)
      REAL*8 ANOVA(13),ALBP(2),B(13,12)
      COMMON WK(56014)
      DATA ALBP/0.05,0.05/
      DATA MDP(3)/1/
```

```
      MDP(1)=MDP1

      DO 10 J=1,N
       T(J)=DFLOAT(J-1)*DELT
       XYW(J,1)=T(J)
       XYW(J,2)=X(J)
       XYW(J,3)=1.0
 10   CONTINUE
C
      CALL RLFOR(XYW,8192,N,RSQ,MDP,ALBP,ANOVA,B,13,PRED,8192,WK,IER)
C
      DO 20 J=1,N
       X(J)=X(J)-PRED(J,1)
 20   CONTINUE

      WRITE(6,1000)MDP(2),IER
      WRITE(6,1001)(B(I,1),I=1,MDP(2)+1)
 1000 FORMAT(1X,'DEGREE OF POLY. :',I5,' ERROR CODE ',I5)
 1001 FORMAT(1X,'COEFFICIENTS :',2E12.4)
      RETURN
      END
C
C HIGH ACCURACY INTEGRATION SCHEME
C  ***DISABLED TO RELEASE DIMENSION SPACE***
C  ***     FOR PROCESSING LARGE FILES      ***
C
C      SUBROUTINE HAINT(H,Y,Z,N)
C
C      REAL*8 Y(8192),Z(8192)
C
C      HT=0.33333333333333333D0*H
C      IF(N-5)7,8,1
C
C  N IS GREATER THAN 5, PREPARATIONS OF INTEGRATION LOOP
C
C    1 SUM1=Y(2)+Y(2)
C      SUM1=SUM1+SUM1
C      SUM1=HT*(Y(1)+SUM1+Y(3))
C      AUX1=Y(4)+Y(4)
C      AUX1=AUX1+AUX1
C      AUX1=SUM1+HT*(Y(3)+AUX1+Y(5))
C      AUX2=HT*(Y(1)+3.875D0*(Y(2)+Y(5))+2.625D0*(Y(3)+Y(4))+Y(6))
C      SUM2=Y(5)+Y(5)
C      SUM2=SUM2+SUM2
C      SUM2=AUX2-HT*(Y(4)+SUM2+Y(6))
C      Z(1)=0.0D0
C      AUX=Y(3)+Y(3)
C      AUX=AUX+AUX
C      Z(2)=SUM2-HT*(Y(2)+AUX+Y(4))
C      Z(3)=SUM1
C      Z(4)=SUM2
C      IF(N-6)5,5,2
C
C  INTEGRATION LOOP
C
C    2 DO 4 I=7,N,2
C      SUM1=AUX1
C      SUM2=AUX2
C      AUX1=Y(I-1)+Y(I-1)
C      AUX1=AUX1+AUX1
```

```
C       AUX1=SUM1+HT*(Y(I-2)+AUX1+Y(I))
C       Z(I-2)=SUM1
C       IF(I-N)3,6,6
C     3 AUX2=Y(I)+Y(I)
C       AUX2=AUX2+AUX2
C       AUX2=SUM2+HT*(Y(I-1)+AUX2+Y(I+1))
C     4 Z(I-1)=SUM2
C     5 Z(N-1)=AUX1
C       Z(N)=AUX2
C       RETURN
C     6 Z(N-1)=SUM2
C       Z(N)=AUX1
C       RETURN
C
C END OF INTEGRATION LOOP
C
C     7 IF(N-3)12,11,8
C
C  N IS EQUAL TO 4 OR 5
C
C     8 SUM2=1.125D0*HT*(Y(1)+Y(2)+Y(2)+Y(2)+Y(3)+Y(3)+Y(3)+Y(4))
C       SUM1=Y(2)+Y(2)
C       SUM1=SUM1+SUM1
C       SUM1=HT*(Y(1)+SUM1+Y(3))
C       Z(1)=0.0D0
C       AUX1=Y(3)+Y(3)
C       AUX1=AUX1+AUX1
C       Z(2)=SUM2-HT*(Y(2)+AUX1+Y(4))
C       IF(N-5)10,9,9
C     9 AUX1=Y(4)+Y(4)
C       AUX1=AUX1+AUX1
C       Z(5)=SUM1+HT*(Y(3)+AUX1+Y(5))
C    10 Z(3)=SUM1
C       Z(4)=SUM2
C       RETURN
C
C    N IS EQUAL TO 3
C
C    11 SUM1=HT*(1.25D0*Y(1)+Y(2)+Y(2)-0.25D0*Y(3))
C       SUM2=Y(2)+Y(2)
C       SUM2=SUM2+SUM2
C       Z(3)=HT*(Y(1)+SUM2+Y(3))
C       Z(1)=0.0D0
C       Z(2)=SUM1
C    12 RETURN
C       END
C
C SMOOTH
C  ***DISABLED TO RELEASE DIMENSION SPACE***
C  ***     FOR PROCESSING LARGE FILES      ***
C
C       SUBROUTINE SMOOTH(XOO,NX,DELT,SM)
C
C       IMPLICIT REAL*8 (A-H,O-Z)
C       REAL*8 XOO(8000),YOO(8000),CC(7999,3),DF(8000),SM
C       COMMON WK(56014)
C       REAL*8 T(8000)
C
C       DO 332 J=1,NX
C        T(J)=DFLOAT(J-1)*DELT*1000
C        DF(J)=XOO(J)
```

```
C  332 CONTINUE
C      CALL ICSSCU(T,XOO,DF,NX,SM,YOO,CC,7999,WK,IER)
C      DO 333 J=1,NX
C       XOO(J)=YOO(J)
C  333 CONTINUE
C      WRITE(6,1900)IER
C 1900 FORMAT(2X,'ICSSCU IER =',I5)
C      RETURN
C      END
```